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Evaluation of Low-Emission Coal Burner Technology on Industrial Boilers. Appendices Volume 2

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16. ABSTRACT

The report gives results of a field evaluation of the Distributed Mixing Burner (DMB) on a 98 kg/hr (215,000 lb/hr) steaming capacity, four-burner, front-wall-fired boiler. Prior to the DMB retrofit, field tests established baseline operating conditions with the pre-NSPS (New Source Performance Standards) burners originally installed in the boiler. Following DMB installation, the boiler was operated and tested with the new burners for 17 months. Under routine operation, the DMBs reduced NOx emissions by about 50%--from the baseline condition of about 0.96 to about 0.46 lb/million Btu (418 to 200 ng/J). Under carefully controlled, optimized conditions, NOx emissions were further reduced about another 20%--to about 0.3 lb/million Btu (131 ng/J). The DMB is a low-NOx pulverized-coal burner for wall-fired boiler applications. It operates under reducing conditions in the primary flame zone to minimize NOx emissions while an overall oxidizing environment is maintained in the furnace to minimize slagging and corrosion. This operation is accomplished by using air ports around the burner throat to provide staged combustion conditions at each individual burner.

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Burners	Stationary Sources	13A
Pulverized Fuels	Distributed Mixing Burners (DMBs)	21D
Combustion		21B
Nitrogen Oxides	Wall-Fired Boilers	07B
	Staged Combustion	

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EVALUATION OF LOW-EMISSION COAL BURNER TECHNOLOGY ON INDUSTRIAL BOILERS

Volume II - Appendices

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APPENDIX A
RESEARCH FURNACES AND TEST EQUIPMENT

The tests of the prototype DMB and the Intervane burner were conducted in three different research furnaces as follows:

- Foster Wheeler Intervane Burner - old EPA Large Watertube Simulator (LWS)
- Initial DMB - original LWS, new LWS
- DMB with Foster Wheeler parameters - new LWS, EER Medium Tunnel (MT)
- Final Prototype DMBs - new LWS

The "old" LWS was erected in the fall of 1976 and was used to test developmental distributed mixing burners under EPA contracts 68-02-1488 and 68-02-2667. The pre-NSPS Foster Wheeler Intervane burner and the initial prototype DMB were both fired in the old LWS in 1979. Testing of the initial prototype DMB was halted in January 1980 when the furnace walls had deteriorated from corrosion. The LWS was rebuilt and upgraded under EPA contract 68-02-3193. The testing of the initial DMB design resumed in the "new" LWS. The new LWS was also used in the evaluation of the DMB with Foster Wheeler parameters and the final prototype DMB designs. The effects of furnace design on burner performance were evaluated by testing the DMB with Foster Wheeler parameters in the EER Medium Tunnel.

A.1 Furnace Designs

The old LWS was designed for full scale simulation of the geometry of a small front wall fired utility watertube boiler with a hopper bottom and a nose above the firing zone. The combustor was 54 feet tall, 28 feet deep, and 16 feet wide. The exhaust products exited directly through openings in the top of the furnace. The old LWS design incorporated a movable back wall to provide for a four-fold variation of the furnace volume, as shown in Figure A-1, and a range of furnace residence times comparable with operating

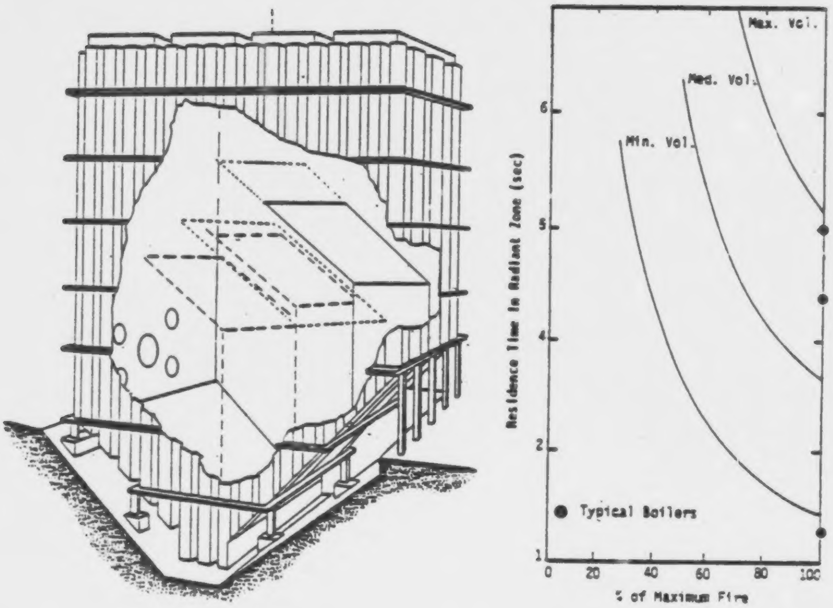


Figure A-1. Variable geometry of the original LWS combustor.

boilers. The outer shell and movable back wall were fabricated from large sections of pre-formed, corrugated mild steel sheet. The structure was stabilized by welded buckstays also formed from sheet steel. The shell was completely unrestrained to thermal growth in the vertical direction, supported at the bottom. The corrugations provide for growth in the horizontal direction. The walls of the furnace were uninsulated and entirely cooled by water by water sprays on the outer surface of the combustion chamber walls. Each spray head on the cooling water manifolds incorporated into the main structural frame was controlled by a solenoid valve operated in a pulsed duration modulation mode, which allowed some flexibility in wall temperature control.

The overall geometry of new LWS was similar to the original design. The burner zone had a rectangular plan area with a 22 foot firing depth and a 16 foot width. The overall furnace height was 50 feet. Several changes were incorporated into the new LWS, including:

- Fixed furnace geometry
- Furnace insulation
- Discrete exhaust duct

The fixed furnace geometry simplified both construction and operation of the rebuilt LWS by eliminating the movable target wall. The characteristics of the new LWS are summarized in Table A-1 and the general furnace configuration is shown in Figure A-2. The 22 foot firing depth was chosen to contain a 150 x 10^6 Btu/hr conventional pulverized coal flame without impingement on the furnace walls.

In large multi-burner boilers, furnace dimensions are based on flame shape and the radiant surface are required for heat absorption. Applying these criteria to a single burner research furnace such as the LWS would result in a narrow tunnel design. However, the fuel/air mixing characteristics and flame stability in a tunnel may be different than in a conventional rectangular furnace. The approach taken with the rebuilt LWS was to design a rectangular furnace with dimensions large enough to avoid

TABLE A-1. NEW LWS FURNACE CHARACTERISTICS

Parameter		Value
Firing		
Configuration	Primary	Single Wall
	Optional	Opposed or Corner
Firing Rate	Minimum	$50x10^6$ Btu/hr
	Maximum	$150x10^6$ Btu/hr
Dimensions		
Firing Depth		22 ft
Width		16 ft
Rear Wall Height		20 ft
Knuckle-to-Nose Heights		27.5 ft
Nose Angle		37° (from Horizontal)
Hopper Angle		52° (from Horizontal)
Height Above Ground Level		35.7 ft
Total Vertical Height		50.5 ft (Pit-to-Top)
Cooled Surface Area		
Burner Zone		804 ft^2
Total Furnace		1951 ft^2
Volume		
Burner Zone		5280 ft^3
Total Furnace		11,544 ft^3 (to Nose)
Insulation		All Sidewalls Knuckle-up to 16 ft
Cooling		Spray-Cooled on All Surfaces

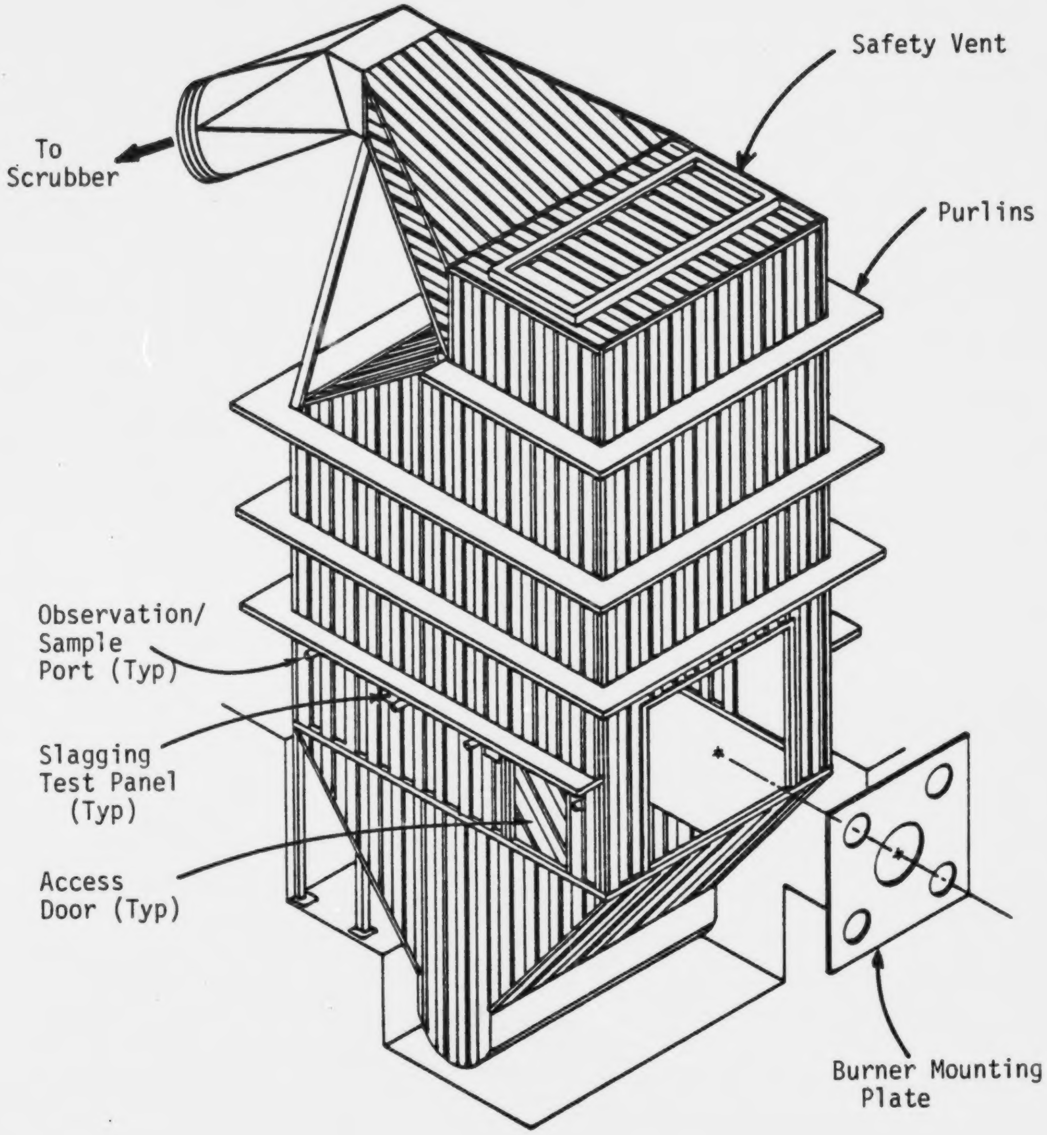


Figure A-2. General configuration of rebuilt LWS.

flame impingement under most test conditions. This results in considerably larger volume and radiant surface area per unit heat release than the demonstration boiler. To adjust the thermal characteristics, insulating refractory was applied to the vertical furnace walls, from the hopper knuckle up 16 feet. The remainder of the furnace was left uninsulated with external water spray cooling the entire shell of the furnace.

A discrete exit for combustion products was incorporated into the rebuilt LWS. The combustion products exit the burner zone of the furnace and pass upward over the nose into the space normally occupied by superheater tubes in a steam generating boiler. Then they enter a six foot diameter spray-cooled exhaust duct which directs the combustion products to a particulate and SO_2 scrubber. The flue gas sampling location is immediately upstream of the scrubber. In the original LWS design, exhaust composition was measured with an array of sampling probes near the nose of the furnace. The exhaust duct not only provides for longer residence time to complete burnout, but permits more representative sampling of the well mixed gas and fly ash stream.

The Medium Tunnel (MT) test facility is an axisymmetric furnace with a maximum firing capacity of 80×10^6 Btu/hr. The furnace is 4.3m (14.0 ft) in diameter and 6.1m (20 ft) long. The cylinder axis is horizontal with test burners mounted in one end of the furnace. The exhaust exits through a 1.5m (5 ft) diameter duct in the center of the target wall. Figure A-3 shows the general configuration of the MT and Table A-2 lists its design parameters and dimensions. To provide a thermal environment similar to large industrial and utility boilers, the MT is partially lined with insulating refractory. The target wall is fully insulated and the cylinder is 50 percent insulated in axial stripes. The entire exterior surface of the MT furnace is continuously sprayed with water much like the LWS, to absorb the heat of combustion.

The characteristics of the three test furnaces are compared in Figure A-4 and Table A-3.

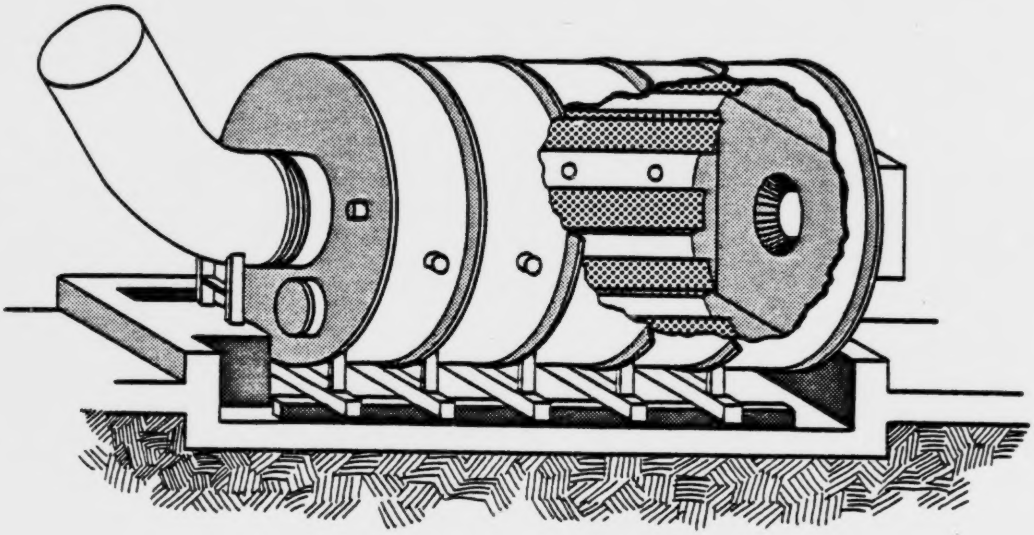


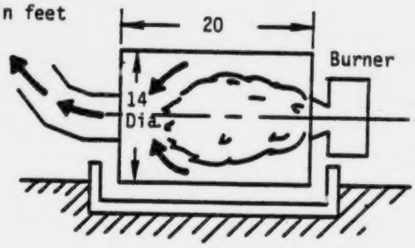
Figure A-3. Cutaway view of Medium Tunnel furnace (MT).

TABLE A-2. EER MEDIUM TUNNEL SPECIFICATIONS

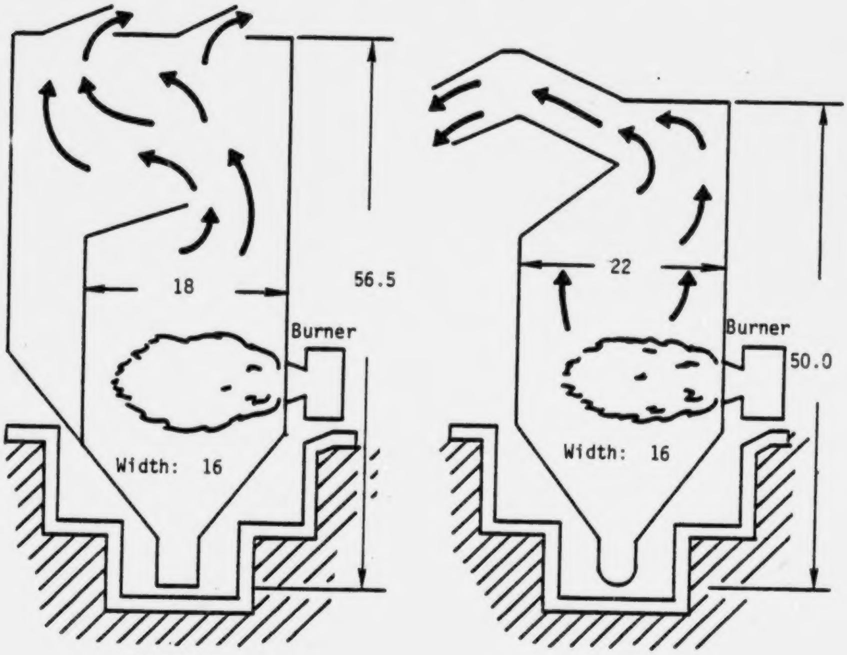
Parameter	EER Medium Tunnel
Capacity (10^6 Btu/hr) [MW]	80 [23.4]
Shape	Horizontal Cylinder
Firing Configuration	Cylinder End
Exhaust	Opposite End
Insulation	46% of Surface Covered
Heat Removal	External Spray Cooling
Diameter (ft) [m]	14 [4.3]
Length (ft) [m]	20 [6.1]
Volume (ft^3) [m^3]	3079 [87.2]
Total Surface Area (ft^2) [m^2]	1188 [110]
Cooled Surface Area (ft^2) [m^2]	644 [59.8]
Heat Release/Cooled Surface Area(Btu/hr-ft^2) [W/m^2]	124×10^3 [3.91×10^5]
Heat Release/Volume (Btu/hr-ft^3) [W/m^3]	26.0×10^3 [2.69×10^5]

* At capacity

Note:
1. All dimensions in feet



Medium Tunnel (MT)



Old LWS

New LWS

Figure A-4. Comparison of research furnaces.

TABLE A-3. COMPARISON OF RESEARCH FURNACES

Furnace	Old LWS	New LWS	MT
Shape	Rectangular with Hopper and Nose	Rectangular with Hopper and Nose	Horizontal Cylinder
Firing Configuration	Front Wall	Front Wall	End
Exhaust	Top	Top	End
Firing Capacity (Btu/hr)	125 x 10^6	150 x 10^6	80 x 10^6
Width (ft)	16	16	14 (dia.)
Firing Depth (ft)	18	22	20
Overall Height (ft)	54	50	---
Cooling	External Water Spray	External Water Spray	External Water Spray
Refractory Insulation in Burner Zone	None	Sidewalls (from knuckle up 16 ft)	50 percent of circumference and 10 percent of target wall
Heat Release/Cooled Surface at 70 x 10^6 Btu/hr Heat Release (Btu/hr-ft2)*	45,000	87,000	125,000
Burner Tested	Development DMBs Intervane Prototype 1	Prototype 1 Prototype 2	Prototype 2

* see text for definition

The heat release per effective cooled surface in the burner zone (Q/A) is an approximately index of furnace heat extraction. Table A-3 lists this parameter for all three furnaces evaluated at the nominal prototype burner firing capacity 70 x 10^6 Btu/hr. For the LWS furnaces, Foster Wheeler's designation of burner zone area was used. This surface is the area of the six-sided box starting at the hopper cycle and extending 10 ft above the top row of burners and includes all cooled surfaces in that volume. For the MT, the cooled surface area on the circumference and end walls was used. Comparing the old and new LWS in Table A-3, the refractory insulation in the new LWS reduces the effective area, which doubles the Q/A. The Q/A for the MT is even higher. The Q/A for the WIPCO furnace is about 130,000 Btu/hr-ft^2 which is slightly higher than the rebuilt LWS and MT.

A.2 Ancillary Equipment

The three test furnaces shared the same basic arrangement of equipment, shown schematically in Figure A-5. The equipment however, has been changed and upgraded throughout the life of the program. The major systems comprising the ancillary equipment include:

- Cooling
- Fuel Supply
- Air Supply
- Exhaust
- Instrumentation

A.2.1 Cooling

The entire external surface of the furnaces are continuously sprayed with water to absorb the heat of combustion. The water is supplied at a rate several times that required for cooling so that all uninsulated surfaces remain in the range 250° to 300°F. Inside the furnace the flames are exposed to an average wall temperature comparable to field-operating boilers (i.e., a balance between uninsulated walls at about 300°F and insulated walls at up to 2400°F). Excess cooling water drains into a sump around the bottom of the

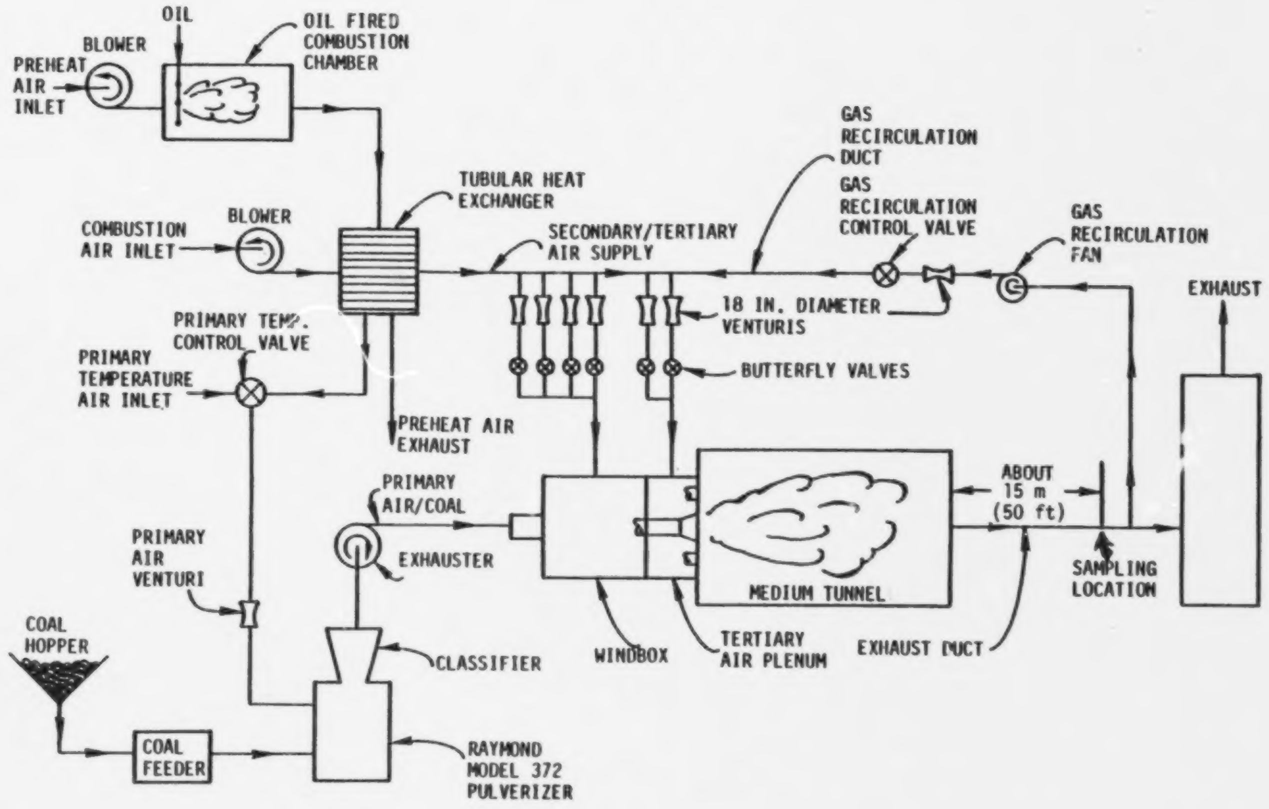


Figure A-5. Piping diagram for burner tests.

furnace and is recycled through a cooling tower. The hopper walls are heavily sprayed with water to avoid buildup of molten ash particles and prevent operations similar to a wet bottom furnace.

A.2.2 Fuel Supply

The furnaces are equipped to fire either distillate oil or coal. However, other equipment can be provided to fire virtually any fuel. Distillate oil is supplied from underground tanks with pumping capacity sufficient to supply a 80 x 10^6 Btu/hr burner. Steam and air are available up to 100 psig for atomization. Two Raymond coal pulverizers are available with capacities of approximately 80 and 150 x 10^6 Btu/hr. These mills are equipped with cyclone classifiers and exhausters. Coal is delivered to the mills through a precision weight belt feeder which provides direct measurement and control of coal firing rate. During testing, the firing rate can be back-calculated from the measurement of air flow rate into the furnace and the residence oxygen in the exhaust also.

A.2.3 Air Supply

Combustion air is supplied by a forced-draft blower through a tubular heat exchanger and into a manifold. The combustion air flow rate is measured and controlled by multiple venturis and dampers. For burners equipped with a common windbox, several venturis can be connected in parallel as shown in Figure A-5. The use of multiple venturis allows accurate flow rate measurement over a wide flow rate range. The other side of the heat exchanger is supplied with hot exhaust from a separate oil-fired combustion chamber. This allows the combustion air preheat temperature to be controlled independently of the performance of the burner firing in the research furnace.

A.2.4 Exhaust

The rebuilt LWS and MT share a common exhaust system. The combustion products pass through an externally spray-cooled duct to a water quench particulate/SO_2 scrubber. The furnace exhaust system was designed to permit a wide range of emission measurements. The sampling location is near the end of a long straight duct meeting EPA specifications for the minimum number of sampling points. Since there is no convective section, the temperature at the sampling point is about 1000°F. Downstream of the sampling location, the exhaust passes into a calcium carbonate scrubber which controls SO_2 and particulate emissions. This system meets all applicable air pollution control regulations.

A.2.5 Instrumentation

The sample train for the continuous gas analyzers is shown in Figure A-6. All materials in contact with the sample are glass, 316 stainless steel or Teflon. These materials are non-reactive with NO at low temperatures. The stainless steel sampling probes are water cooled, and small cyclones adjacent to the probe remove particulate matter and condensed water. The sample is then transported to the control room through a Teflon line where it is filtered and dried. The sample pump is Teflon lined and the sample flow rate is maintained at several times the instruments' requirements to minimize response time. Excess sample flow is bypassed to a vent. Commercial gas analyzers are used for measurements of O_2, CO_2, CO, NO/NO_x and SO_2 and are listed in Table A-4. The accuracy of each instrument is maintained by frequent calibration with zero and certified calibration gases.

The signals from the gas analyzers, venturis, weight belt, thermocouples and other instruments are interfaced with a computerized on-line data reduction system and data is printed out in convenient engineering units. This assists in the data analysis and allows test conditions to be established rapidly and accurately.

A.3 Sorbent Injection Equipment

The sorbent injection system, as shown in Figure A-7 consists of a volumetric feeder, hopper, and air injection system. The feeder is a commercial volumetric twin screw feeder manufactured by K-tron. The air

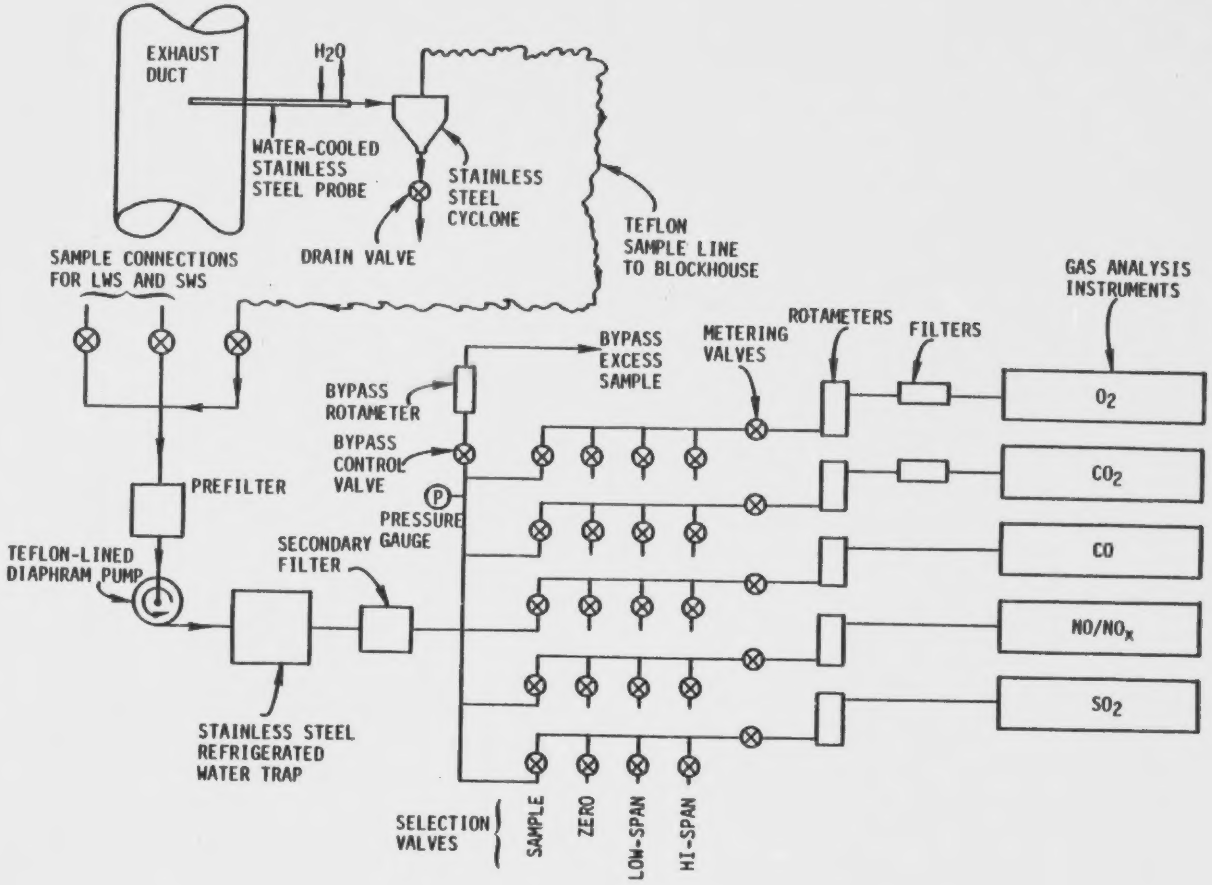
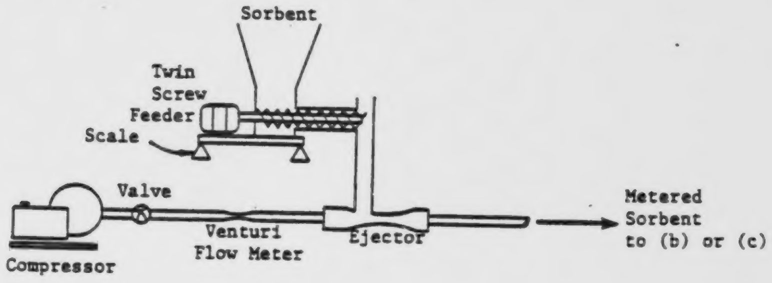


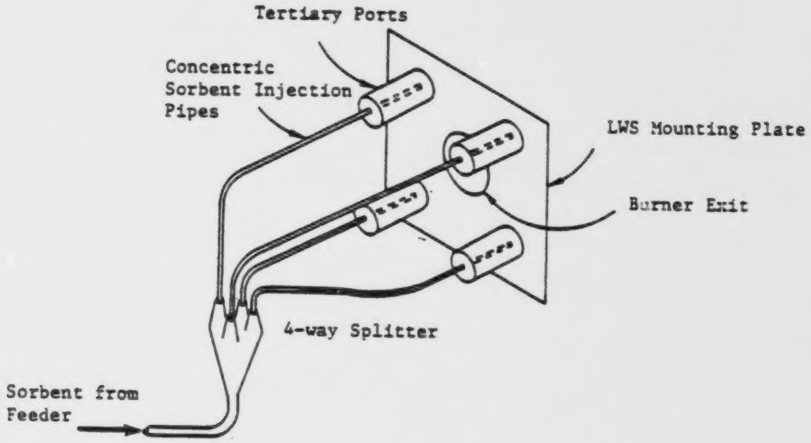
Figure A-6. Sample train schematic.

TABLE A-4. INSTRUMENTATION AND MEASUREMENTS

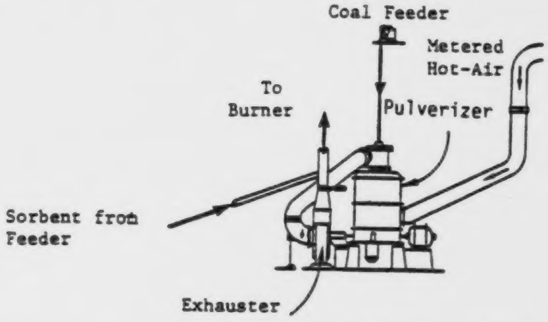
Parameter	Method	Record	Parameter	Method	Record
Burner settings	Manual	Manual	Flame characteristics	Manual and color video	Manual
Air flow rates	Calibrated venturis				
Temperatures	Thermocouple	Computer	O_2	Taylor, Paramagnetic	Computer and Strip Chart
			CO	Anarad, NDIR	
Coal flow rates	Weight belt feeder and back-calculate from air flow rates and excess O_2	Computer	CO_2	Anarad, NDIR	
			NO_x	Beckman, Chemiluminescent	
			SO_2	TECO, Pulsed Fluorescent; and DuPont, Ultraviolet	
Coal fineness	ASME Sieve method	Manual			
Coal Composition	Ultimate	Manual	Particulate		
Stoichiometry	Calculate	Computer	Mass	High-Volume filter	Manual
			Size distribution	Andersen, Cascade impactor	Manual
			Composition	Ultimate Analysis	Manual
			Burner Pressure	Magnahelic	Manual



a) Sorbent Feed System



b) Sorbent Injection through Tertiary Air Ports



c) Sorbent Injection with Coal

Figure A-7. Schematic representation of sorbent injection system.

injection system consists of a compressor, a venturi to monitor flow and an ejector. The sorbent was injected at two locations, directly at the outlet of the pulverizer or through a four-way splitter into the tertiary air ports. Sorbent was injected through pipes located on the axis of each tertiary air port. The volumetric feeder was calibrated with each sorbent material to determine the rate of sorbent flow for a range of feeder speeds. In addition, during each injection test, direct feed rate was determined by mounting the feeder and hopper assembly on a scale to determine weight change over time.

The SO_2 sample system, shown in Figure A-8 was utilized during the commercial burner tests. A phase discrimination probe is used. This probe is designed to effectively separate particulate matter of the central stream of sample gas from the sample that passes through the SO_2 analyzer. This separation minimizes the SO_2 scrubbing effect caused by particulate in the gas stream when sorbent is present. The sample passes through a heated sample line and a heated filter to polish the gas sample of any remaining particulate matter while avoiding any scrubbing reactions. The entire SO_2 sample system was maintained at temperatures above the flue gas dewpoint to prevent any condensation. Therefore, the SO_2 measurement is determined on a wet basis. The remaining central stream of the gas sample passes through a condenser and delivers a sample for the remaining instruments. To relate the absolute SO_2 concentrations, determined on a wet basis, to the remaining instrumentation analyzing dry, conditioned stack gas, the following relationship was used:

$$\text{ppm (dry)} = \text{ppm (wet)} \times \frac{100}{(100 - \%\text{ moisture in stack gas})}$$

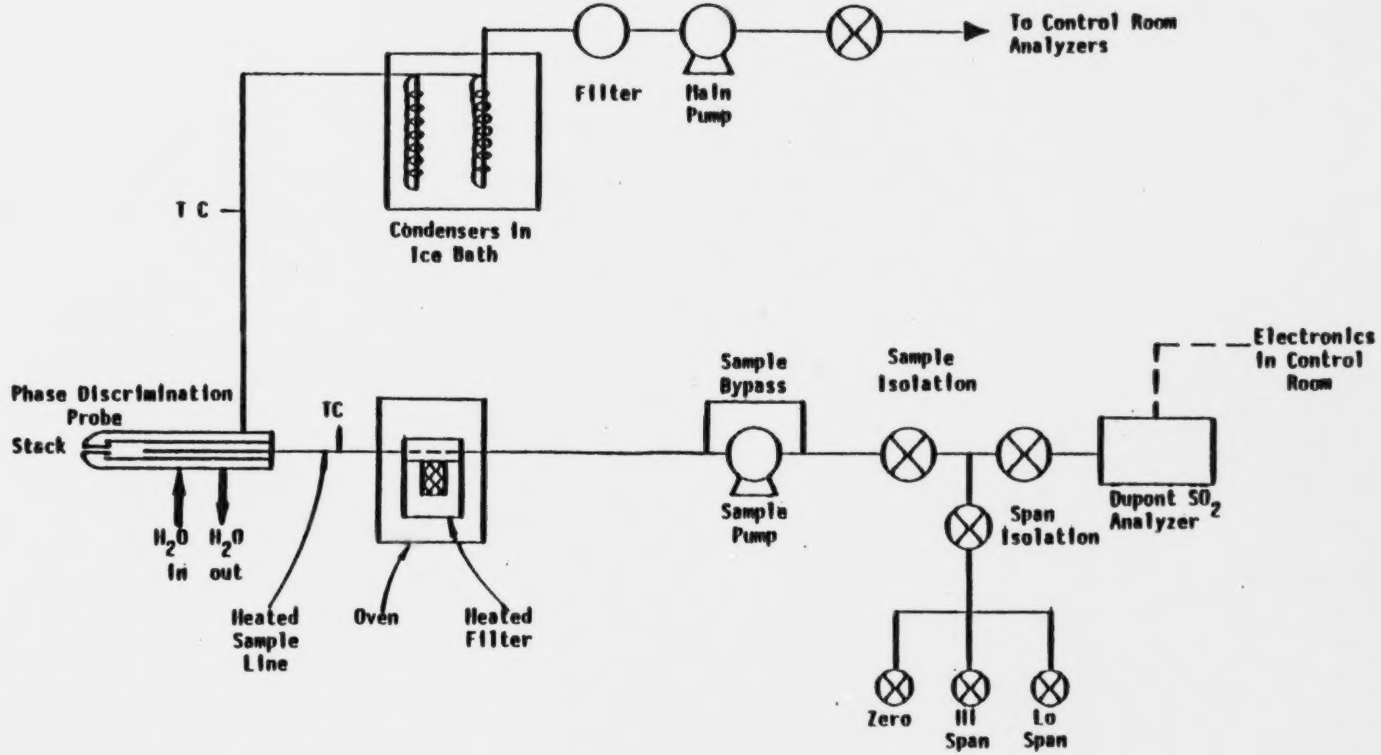


Figure A-8. Schematic of sampling system for active particle laden gas streams.

APPENDIX B
FUELS AND SORBENTS USED DURING PROTOTYPE BURNER TESTS

B.1 Test Fuels

Coals from three different mines were used in the tests of the prototype distributed mixing burners and the Foster Wheeler Intervane burner in the research furnaces: Utah coal from the Starpoint 1 and 2 mines in Wattis, Utah; Indiana coal from the Three States Trucking mine in Huntingburg, Indiana; and Illinois coal from the Crown II mine in Virden, Illinois. The Utah coal has been used at EER as the base fuel for most of the low-emission, high efficiency burner development tests. It was used in the prototype burner tests to provide a direct comparison of prototype DMB performance with a wide data base of other burners. The Indiana coal was the fuel being fired at the WIPCO boiler at the beginning of this program and was designated as the WIPCO host site design coal. However, WIPCO did not have a long term coal contract. Small quantities of coal were purchased from several mines based primarily on cost ($/Btu). Fuels were obtained from several suppliers in Missouri and Illinois. As an illustration of the range of coals fired at WIPCO Pearl Station, Table B-1 lists the range of coal composition measured during the baseline field tests during the summer of 1981. The Illinois coal had a high sulfur content was used during a limited series of sorbent injection tests with the DMB with Foster Wheeler parameters to evaluate sorbent injection for high sulfur fuels.

The various tests of burners in research furnaces for this program spanned a period of about four years. As a result, the test fuel supply was subject to weathering and replacement/replenishment of the stock pile. Compositions of the Utah, Indiana and Illinois coals used during the research furnace tests are summarized in Tables B-2, B-3, and B-4, respectively. The Utah and Indiana coals were used in tests throughout the program. Analyses of coal composition were obtained prior to each burner test series with the

TABLE B-1. COAL COMPOSITION FIRED AT WIPCO DURING BASELINE FIELD TEST

	Based On Samples		
	Range	Average	Standard Deviation
Moisture Content	5.84-17.73	8.35	2.41
Calorific Value (Btu/lb)*			
As Received	9,622-11,710	10,670	758
Dry	11,192-12,691	12,022	526
Ultimate Analysis (% dry)			
Carbon	60.49-72.47	65.92	2.32
Hydrogen	4.23-5.06	4.44	0.69
Nitrogen	1.12-1.53	1.37	0.09
Sulfur	2.73-5.61	3.63	0.66
Ash	9.96-20.90	13.38	2.36
Oxygen (by difference)	5.10-14.23	10.76	2.60

* 1.0 Btu/lb = 2.32 kJ/kg

TABLE B-2. COMPOSITION OF UTAH COAL USED DURING RESEARCH FURNACE TESTS

COAL	UTAH 1		UTAH 2		UTAH 3		UTAH 4	
REPORTING BASIS	AS REC'D	DRY	AS REC'D	DRY	AS REC'D	DRY	AS REC'D	DRY
PROXIMATE (WT %)								
MOISTURE	4.58	0.00	2.84	0.00	7.79	9.30	9.30	0.00
ASH	8.76	9.18	7.22	7.43	7.26	7.87	8.30	9.15
VOLATIVES	37.87	39.69	41.95	43.18	40.57	44.00	39.34	43.37
FIXED CARBON	48.79	51.13	47.99	49.39	44.38	48.13	43.06	47.48
CALORIFIC VALUE (BTU/LB)								
BTU/lb	12,333	12,924	12,731	13,103	12,150	13,176	11,835	13,049
MMF BTU/lb		14,370		14,273		14,425		14,504
MAF BTU/lb		14,230		14,155		14,302		14,363
ULTIMATE (WT %)								
MOISTURE	4.58	0.00	2.84	0.00	7.79	0.00	9.30	0.00
CARBON	63.51	66.56	71.70	73.80	63.12	73.88	66.04	72.80
HYDROGEN	5.19	5.44	5.63	5.80	5.10	5.53	5.03	5.55
NITROGEN	1.52	1.59	1.46	1.50	1.58	1.71	1.12	1.23
SULFUR	0.68	0.71	0.85	0.87	0.71	0.77	0.66	0.73
ASH	8.76	9.18	7.22	7.43	7.26	7.87	8.30	9.15
OXYGEN*	15.76	16.52	10.30	10.60	9.44	10.24	9.55	10.54

* OXYGEN BY DIFFERENCE

TABLE B-3. COMPOSITION OF INDIANA COAL USED DURING RESEARCH FURNACE TESTS

COAL	INDIANA 1		INDIANA 2		INDIANA 3		INDIANA 4	
REPORTING BASIS	AS REC'D	DRY	AS REC'D	DRY	AS REC'D	DRY	AS REC'D	DRY
PROXIMATE (WT %)								
MOISTURE	6.98	0.00	5.75	0.00	16.35	0.00	9.17	0.00
ASH	11.77	12.66	11.15	11.82	8.43	10.08	11.88	13.08
VOLATIVES	38.15	41.01	36.47	38.69	26.88	32.13	28.40	31.26
FIXED CARBON	43.10	46.33	46.63	49.49	48.34	57.79	50.55	55.66
CALORIFIC VALUE (BTU/LB)								
BTU/lb	11,779	12,663	11,527	12,230	10,990	13,138	10,688	11,766
MMF BTU/lb		14,780		14,102		14,809		13,745
MAF BTU/lb		14,499		13,869		14,611		13,536
ULTIMATE (WT %)								
MOISTURE	6.98	0.00	5.75	0.00	16.35	0.00	9.17	0.00
CARBON	65.17	70.06	64.91	68.87	62.63	74.87	62.36	68.61
HYDROGEN	4.65	5.00	4.84	5.14	3.56	4.26	3.75	4.13
NITROGEN	1.54	1.66	1.37	1.45	1.05	1.26	1.17	1.28
SULFUR	2.87	3.08	2.41	2.56	1.59	1.90	1.33	1.46
ASH	11.77	12.66	11.15	11.82	8.43	10.08	11.88	13.08
OXYGEN*	7.02	7.54	9.57	10.16	6.39	7.63	10.38	11.44

* OXYGEN BY DIFFERENCE

TABLE B-4. COMPOSITION OF ILLINOIS COAL USED DURING RESEARCH FURNACE TESTS

COAL	ILLINOIS	
REPORTING BASIS	AS REC'D	DRY
PROXIMATE (WT %)		
MOISTURE	16.89	0.00
ASH	9.37	11.28
VOLATIVES	35.64	42.88
FIXED C	38.10	45.84
CALORIFIC VALUE (BTU/lb)		
BTU/lb	10,480	12,610
MMF BTU/lb		14,494
MAF BTU/lb		14,213
ULTIMATE (WT %)		
MOISTURE	16.89	0.00
CARBON	57.85	69.61
HYDROGEN	4.09	4.92
NITROGEN	1.03	1.24
SULFUR	3.30	3.97
ASH	9.37	11.28
OXYGEN*	7.46	8.98

* OXYGEN BY DIFFERENCE

numbered designations, i.e. Utah 2, representing the coal for a particular test series. These designations are defined for each coal in Table B-5. The shipment number refers to the consecutive number of the coal relative to this program, while the designation of the coal refers to the analysis of the coal used for a particular series of tests. For the Indiana coal in particular, Indiana 1 and 2 designations refer to the same coal shipment that was used for two test series over a year apart.

B.2 Sorbents Materials

Two sorbents were used to evaluate SO_2 reduction potential with the industrial prototype burners. A processed limestone, Vicron 45-3, and a processed hydrated lime, Colton lime, were used. Both materials are commercially available high-calcium materials used in the development of LIMB technology at EER. They were chosen because quality control in their processing assures a consistent material for all batches ordered. The typical characteristics of these two sorbents are listed in Table B-6 and the corresponding size distributions are shown in Figure B-1. Vicron 45-3 is 99 percent pure $CaCO_3$, while the Colton hydrated lime is 96 percent pure $Ca(OH)_2$. Mass median diameters were 9.8 and 4.0 microns, respectively. The use of these processed materials minimizes interferences due to impurities, although the commercial use of such process sorbents may not be economically feasible.

TABLE B-5. DESIGNATION OF COALS USED IN RESEARCH FURNACES

COAL DESIGNATION	SHIPMENT NUMBER	TEST INITIATED	BURNER(S)	RESEARCH FURNACE(S)
UTAH 1	1	9/79 11/79	INTERVANE INITIAL DMB	ORIGINAL LWS ORIGINAL LWS
UTAH 2	2	12/80 3/81	INITIAL DMB DMB WITH FW PARAMETERS	REBUILT LWS REBUILT LWS
UTAH 3	3	10/81	DMB WITH FW PARAMETERS	MT
UTAH 4	4	10/83	FINAL DMBs	REBUILT LWS
INDIANA 1	1	11/79	INITIAL DMB	ORIGINAL LWS
INDIANA 2	1	12/80 3/81	INITIAL DMB DMB WITH FW PARAMETERS	REBUILT LWS REBUILT LWS
INDIANA 3	2	10/81	DMB WITH FW PARAMETERS	MT
INDIANA 4	3	10/83	FINAL DMBs	REBUILT LWS
ILLINOIS	1	3/81	DMB WITH FW PARAMETERS	REBUILT LWS

TABLE B-6. TYPICAL CHARACTERISTICS OF SORBENTS

		Physical Properties			Elemental Ash (Wt %)									
Sorbent	Theoretical Characteristics	Median Diameter (μm)	Density (gm/cm^3)	LOI @ 1000°C (Wt %)	CaO	Fe_2O_3	Al_2O_3	Na_2O	MgO	K_2O	SiO_2	TiO_2	P_2O_5	SO_3
Vicron 45-3	$CaCO_3$	9.8	2.706	42.49	55.64	0.08	0.03	0.01	0.54	<0.01	0.20	<0.01	0.01	0.02
Hydrated Lime	$Ca(OH)_2$	4.0	2.279	22.91	72.67	0.15	0.40	0.01	0.42	0.06	7.06	0.02	0.01	0.07

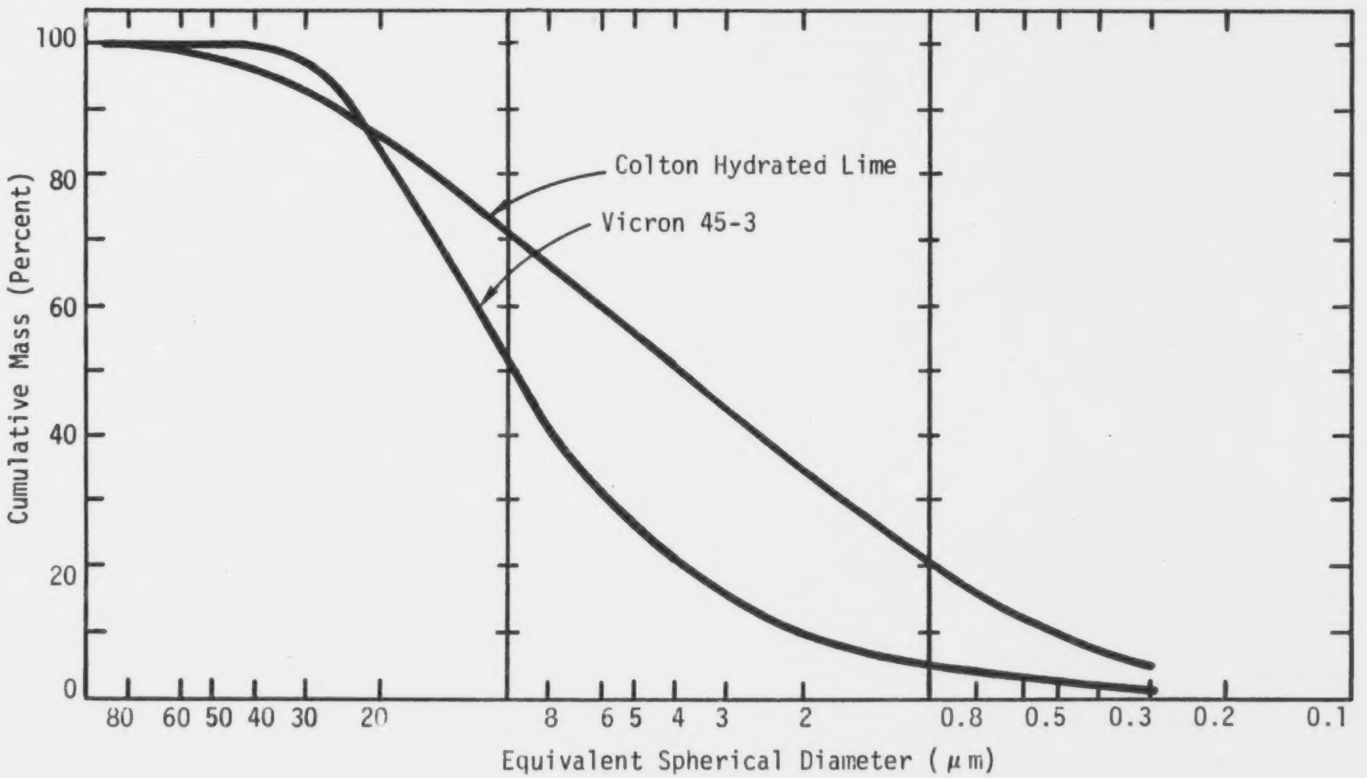


Figure B-1. Sorbent particle size distributions.

APPENDIX C
MEASUREMENTS PROTOCOL

To ensure that the measurements conducted in this program were accurate, complete and appropriate, a measurements plan was prepared at the beginning of the program. It was documented in a comprehensive report submitted to EPA in 1980 and in the Second Annual Report. This Appendix summarizes the measurement and data quality assurance/control (QA/QC) procedures. It should be noted that this program was initiated prior to the development of the current EPA QA/QC program. However, due to the importance of the program results, a QA/QC program approximating the current requirements was conducted. The following subsection summarizes the measurement procedures used during the burner tests in research furnaces (which were discussed in Section 3) and the field tests (discussed in Sections 2 and 4). Subsection D.2 discusses the field measurement system. The measurement system for the research furnace tests was discussed in Appendix B.

C.1 Measurements Summary

Separate measurement procedures were developed for the research furnace and field tests to ensure that their respective test objectives were achieved. The burner tests in the research furnaces were developmental. Prototype DMBs were tested over the operating ranges of the field boiler and the design parameters were adjusted to produce an optimum balance of flame stability, efficiency and emissions. A commercial burner similar to the original equipment burners on the field boiler were tested also to establish a baseline. The measurements protocol for the research furnace tests was structured to include measurement of key test conditions and test outputs with accuracy and repeatibility sufficient to allow the relationships between burner adjustments and performance to be determined. The tests in the field operating boiler constitute the actual DMB evaluation. The initial tests involved the original equipment burners and established a baseline burner/boiler performance. The DMB field test results provide an index of the performance of the DMB in field operating boilers and maybe used as inputs to air quality plans. The measurements protocol for the field tests was structured to provide more detail and complete measurement methods and (where possible) measurements were referenced to absolete or NBS standards.

Figure C-1 shows the overall organization of the measurements protocol. The measurements were organized into the following categories of increasing complexity:

- standard measurement format
- detailed measurement format
- effluent stream analysis

In addition, corrosion measurements were conducted as part of the field tests.

The standard measurement format was the minimum set of measurements and was applied to all research furnace and field tests. It includes measurement of the test inputs necessary to specify operating conditions as well as routine measurements of output parameters. Table C-1 and C-2 list the parameters and measurement methods for the research furnace and field tests respectively. Where practical, continuous measurements were selected so that the durations of specific tests were limited by the dynamics of the burner/furnace systems rather than the maximum data acquisition rate. For example, gas phase species in the combustion products were measured with continuous gas analyzers. During the research furnace tests and field tests where burner performance was evaluated at specific test conditions, the entire standard measurement format was applied. Portions of the standard measurement format were used to evaluate performance under non-standard conditions or during brief check-out tests. The field tests also included extended test periods with original equipment and low emission burners. The standard measurement format was applied continuously during the extended test periods.

The detailed measurement format included all of the measurements in the standard measurement format plus intermittent measurement of certain output

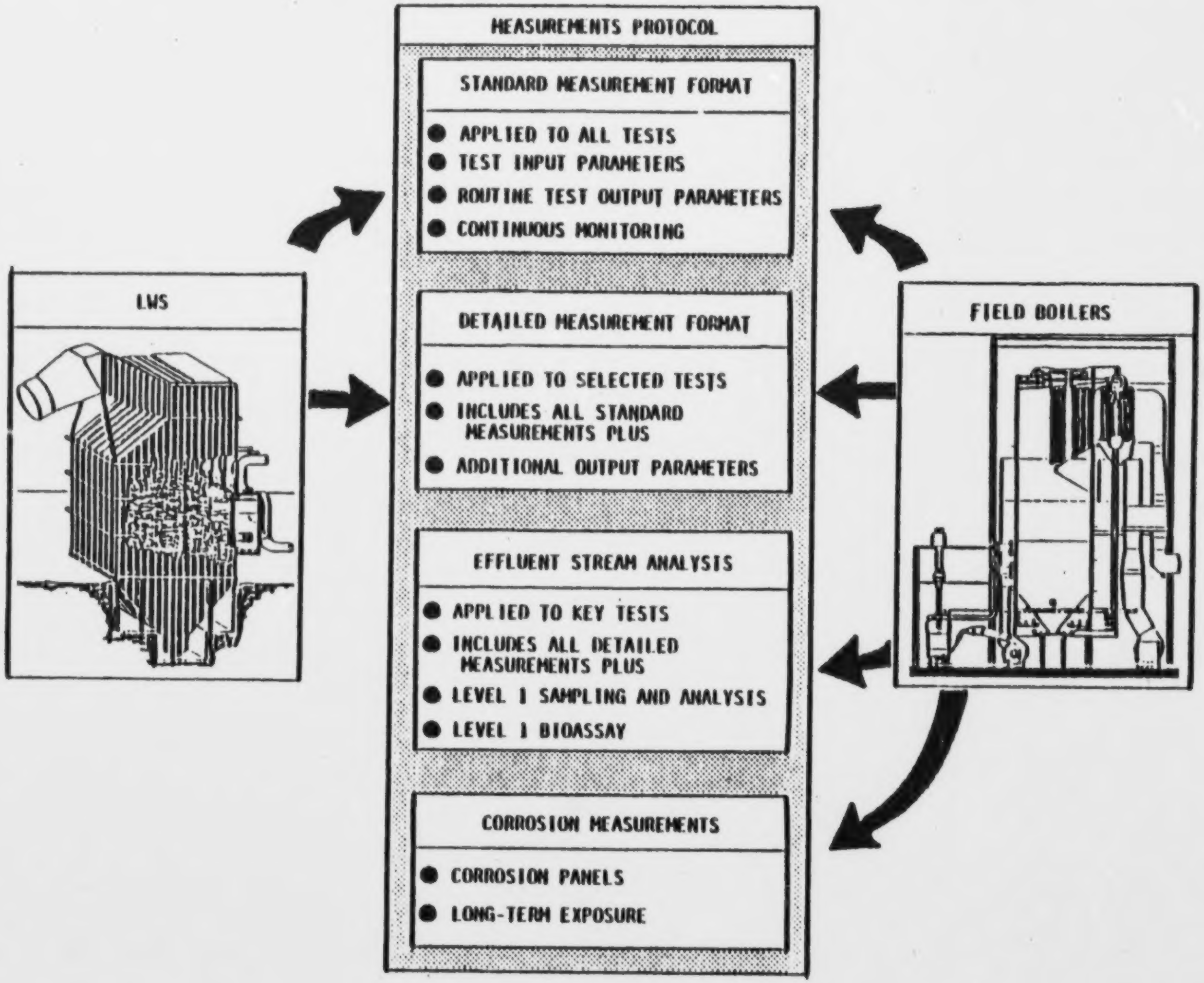

LWS
MEASUREMENTS PROTOCOL
STANDARD MEASUREMENT FORMAT
● APPLIED TO ALL TESTS
● TEST INPUT PARAMETERS
● ROUTINE TEST OUTPUT PARAMETERS
● CONTINUOUS MONITORING
DETAILED MEASUREMENT FORMAT
● APPLIED TO SELECTED TESTS
● INCLUDES ALL STANDARD MEASUREMENTS PLUS
● ADDITIONAL OUTPUT PARAMETERS
EFFLUENT STREAM ANALYSIS
● APPLIED TO KEY TESTS
● INCLUDES ALL DETAILED MEASUREMENTS PLUS
● LEVEL 1 SAMPLING AND ANALYSIS
● LEVEL 1 BIOASSAY
CORROSION MEASUREMENTS
● CORROSION PANELS
● LONG-TERM EXPOSURE
FIELD BOILERS

Figure C-1. Measurements protocol organization.

TABLE C-1. STANDARD MEASUREMENT FORMAT SUMMARY (RESEARCH FURNACE)

Test Conditions		Test Outputs	
Parameter	Measurement Method	Parameter	Measurement Method
Furnace Design	Direct Measurement	Flame Characteristics	Direct Observation and/or Color Video
Burner Design		Length	
Burner Adjustments		Width	
Registers		Standoff	
Dampers		Stability	Flame Scanner
Others		Gas Phase Species	
Fuel		O_2	Continuous Analyzers
Composition	Obtain Sample (analyze under detailed format)	NO/NO_x	
Flow Rate	Weigh belt feeder or calculate from airflow and excess O_2	CO	
		CO_2	
		Other	
Combustion Air			
Flow Rate	Venturis	Smoke	Direct Observation
Temperature	Thermocouples	Windbox Pressure	Pressure Gauge
Distribution	Venturis or Internal Flowmeters	Burner Temperatures	Thermocouples

TABLE C-2. STANDARD MEASUREMENT FORMAT SUMMARY (FIELD)

Test Conditions		Test Outputs	
Parameter	Measurement Method	Parameter	Measurement Method
Furnace Design	Direct Measurement	Flame Characteristics	Direct Observation and/or Color Video
Burner Design		Length	
Burner Adjustments		Width	
Registers		Standoff	
Dampers		Stability	Flame Scanner
Others		Gas Phase Species	
Fuel		O_2	Continuous Analyzers
Composition	Obtain Sample (analyze under detailed format)	NO/NO_x	
		CO	
Flow Rate	Weigh belt feeder or calculate from airflow and excess O_2	CO_2	
		Other	
Combustion Air			
Flow Rate	Boiler Instrumentation	Thermal Performance	Boiler Instrumentation
Temperature	Boiler Instrumentation	Smoke	Direct Observation
Distribution	Internal Flowmeters or Boiler Instrumentation	Windbox Pressure	Boiler Instrumentation
		Burner Temperatures	Thermocouples

parameters. Tables C-3 and C-4 list the parameters in measurement methods for the research furnace and field tests respectively. The detailed measurement format was applied to selected test conditions to more fully characterize burner performance. During the research furnace tests, the detailed measurement format was applied to the original equipment burner tests and selected tests of the prototype DMBs under key operating conditions (optimized performance, etc). During the field tests, the detailed measurement format was applied in the same manner to map burner/boiler performance. It was applied during the extended period tests to obtain index of performance variability. The detailed measurement format included manual measurements of several parameters, including particulate mass, particulate size distribution and SO_3.

The effluent stream analysis was the most complex measurement format and was applied to only one test condition: the nominal operating condition of the field boiler with the baseline Intervane burners. These measurements included a EPA level 1 environmental assessment including bioassay as well as certain other emission measurements. Figure C-2 shows the basic level one sampling and analysis scheme for solids, liquids and slurries. It should be noted that although the EPA Level 1 test was conducted, a Quality Assurance audit indicated that the results could not be used due to extensive Quality Control problems.

Corrosion measurements were made to ensure that the DMBs do not contribute to furnace wall corrosion. These measurements were conducted only in the field boiler since the duration of the research furnace test was too short to assess corrosion rates accurately. Corrosion panels were installed prior to the DMB installation so that data was obtained with the original equipment burners. Figure C-3 illustrates the design and installation of the corrosion panels on the field evaluation boiler. During the DMB installation, the tube thickness was measured to establish the baseline corrosion rate. Periodically, throughout the DMB test period, tube thickness was measured again to establish a corrosion rate for the DMB. Thus, these data provide direct comparisons of the corrosions rates for the two burner systems.

TABLE C-3. DETAILED MEASUREMENT FORMAT SUMMARY (RESEARCH FURNACES)

TEST CONDITIONS		TEST OUTPUTS	
PARAMETER	MEASUREMENT METHOD	PARAMETER	MEASUREMENT METHOD
Fuel		Particulates	
Composition	ASTM Methods (ultimate and proximate)	Total Mass	EPA Method 5
	EER Laboratory Methods (ultimate)	Composition	EER Laboratory Methods (ultimate)
Size Distribution	ASME Method	Size Distribution	Andersen Cascade Impactor
		Carbon Balance	
		CO, CO_2	Standard Measurement Format
		Hydrocarbons	Hot F. I. D.
		Particulate	Same as Above
		Bottom Ash	Grab sample and EER laboratory ultimate analysis
		Coal	Same as at left
		Sulfur Balance	
		SO_2	Continuous Monitor and/or EPA Method 6
		SO_3	EPA Method 8 and Controlled Condensation
		Particulate	Same as above
		Bottom Ash	Same as above
		Coal	Same as at Left

TABLE C-4. DETAILED MEASUREMENT FORMAT SUMMARY (FIELD)

Test Conditions		Test Outputs	
Parameter	Measurement Method	Parameter	Measurement Method
Fuel		Particulates	
Composition		Total Mass	EPA Method 5
Ultimate	ASTM Method D271-48		
Proximate			
	EER Laboratory Methods (Ultimate)	Composition	EER Laboratory Methods (Ultimate)
Size Distribution	ASME Method PTC 3.2 ASTM D410-38 and ASTM D197-30	Size Distribution	Andersen Cascade Impactor
		Carbon Balance	
		CO, CO_2	Standard Measurement Format
		Hydrocarbons	Hot F. I. D.
		Particulate	Anderson Cascade Impactor
		Bottom Ash	Grab Sample and EER Lab. Ultimate Analysis
		Coal	ASTM Methods D410-38, D197-30, and D271-48
		Sulfur Balance	
		SO_2	Continuous Monitor and/or EPA Method 6
		SO_3	EPA Method 8 and Controlled Condensation
		Particulate	Anderson Cascade Impactor
		Bottom Ash	Grab Sample and EER Lab. Ultimate Analysis
		Coal	ASTM Methods
		Thermal Balance	ASME Method
		Gas Concentrations in the Furnace	Continuous Monitors (See Table C-5)

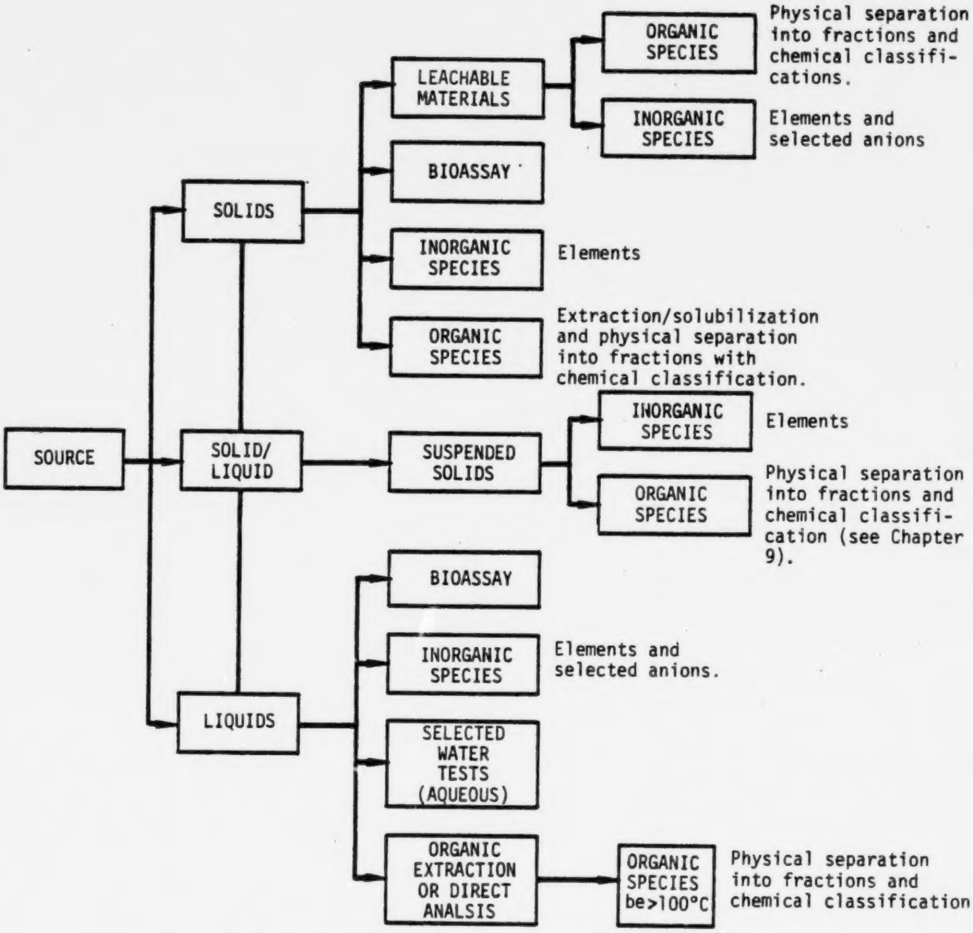

SOURCE
SOLIDS
SOLID/ LIQUID
LIQUIDS
LEACHABLE MATERIALS
ORGANIC SPECIES
Physical separation into fractions and chemical classifications.
INORGANIC SPECIES
Elements and selected anions
BIOASSAY
INORGANIC SPECIES
Elements
ORGANIC SPECIES
Extraction/solubilization and physical separation into fractions with chemical classification.
SUSPENDED SOLIDS
INORGANIC SPECIES
Elements
ORGANIC SPECIES
Physical separation into fractions and chemical classification (see Chapter 9).
BIOASSAY
INORGANIC SPECIES
Elements and selected anions.
SELECTED WATER TESTS (AQUEOUS)
ORGANIC EXTRACTION OR DIRECT ANALSIS
ORGANIC SPECIES be>100°C
Physical separation into fractions and chemical classification

Figure C-2. Basic Level 1 sampling and analytical scheme for solids, slurries and liquids.

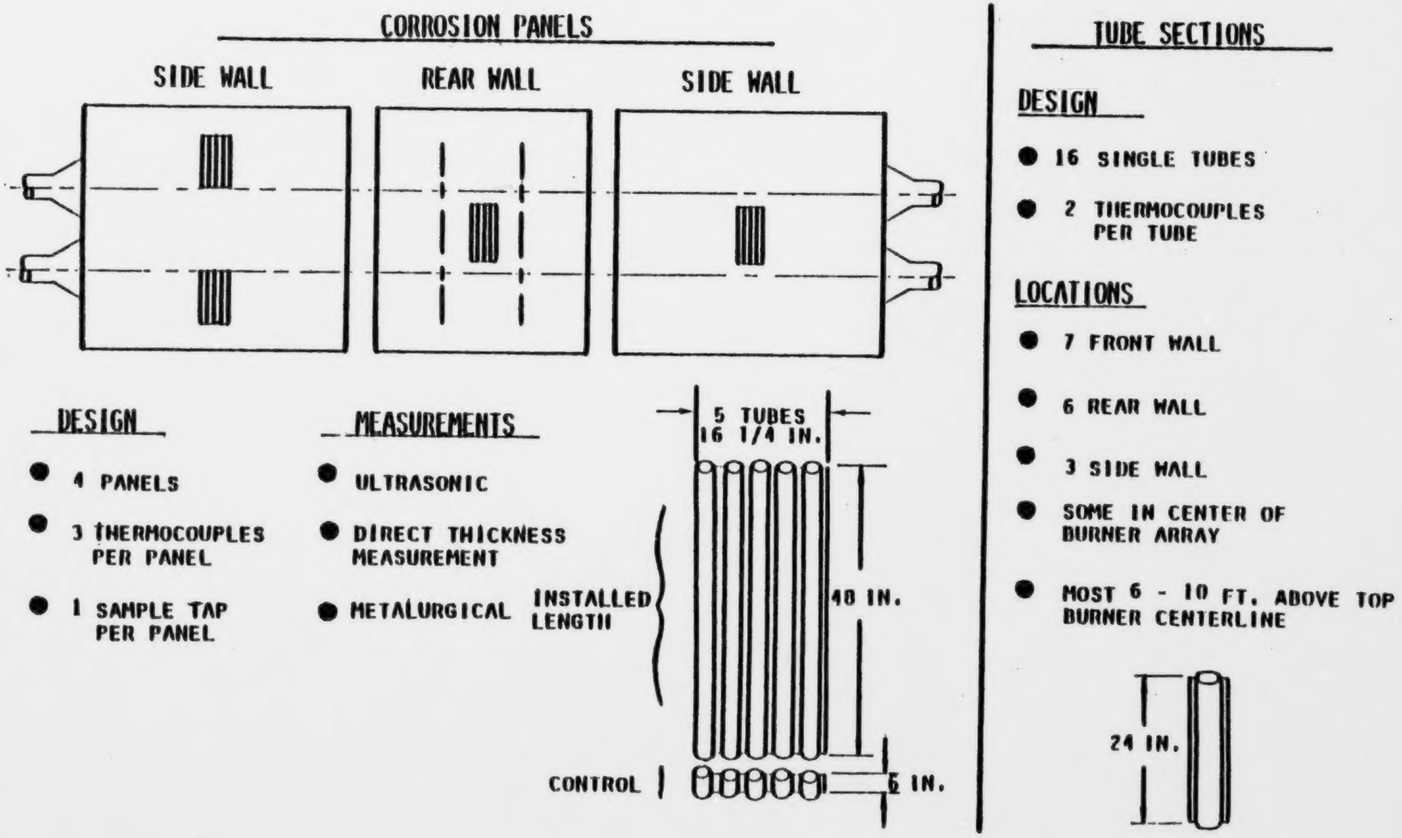


Figure C-3. Corrosion panel installation on the field evaluation boiler.

During the research furnace tests, data quality was maintained by following the test procedures in the protocol. However, the increased importance of the field tests required a quality control plan. To ensure that the emission measurements were accurate, EPA methods were used for the primary measurement methods or as reference methods. In addition, the continuous monitoring system was constructed, calibrated, verified and operated according to EPA performance specifications two and three. The field tests were also subjected to a quality assurance audit by an independent EPA contractor.

C.2 Measurement System at the Field Evaluation Boiler

A complete measurement system capable of conducting all measurements required by the standard and the detailed measurement formats was constructed and installed on the WIPCO boiler. It was used to conduct the baseline tests as well as the DMB tests. This section describes the design of the continuous monitoring system and the quality assurance procedures conducted to ensure accurate data.

C.2.1 Continuous Monitoring System

The measurement system included continuous gas analyzers for measurement of NO/NO_x, CO, CO_2, O_2, hydrocarbons and SO_2. Table C-5 lists the instruments and the nominal full-scale range. These instruments are the same as those in service on the research furnaces except for the NO_x and SO_2 analyzers. The TECO NO_x analyzer is preferred over the Beckman (which is currently in use on the LWS) because of its lower sensitivity to background gas composition variations. This is due to the low pressure reaction chamber used on the TECO. The DuPont SO_2 analyzer is preferred over the TECO (which is currently in use on the LWS) because of its greater flexibility and potentially greater accuracy in measuring SO_2 in the presence of active SO_2 sorbent.

The instrument ranges listed in Table C-5 were selected to exceed the maximum gas concentrations which were expected to be measured by a small

TABLE C-5. CONTINUOUS GAS ANALYSIS INSTRUMENTS

Gas Measured	Type of Instrument	Manufacturer	Model No.	Full-Scale Range
NO, NO_x	Chemiluminescent	Thermo Electron Corp. (TECO)	10 AR	1000 ppm
CO	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	500 ppm
CO_2	Nondispersive Infrared (NDIR)	Anarad, Inc.	AR500R	25%
O_2	Paramagnetic	Taylor Servomex	Type OA 272	10%
H_xC_y	Flame Ionization	Beckman Instruments, Inc.	402	50 ppm (C_3H_8)
SO_2(1)	UV Absorption	DuPont	400	5000 ppm
SO_2(2)	Pulsed Fluorescence	Thermo Electron Corp. (TECO)	40	5000 ppm

(1) Preferred Instrument
(2) Alternate Instrument

margin. Each instrument is calibrated by three gases: a zero gas and two span gases at approximately 50 and 90 percent of span. Table C-6 lists the span gases for each instrument. As part of the quality control plan, the calibration gases were prepared according to The EPA Protocol. This involves traceability to NBS certified standards. In cases where the appropriate NBS standards were not available, Gas Manufacturer's Primary Standard (GMPS) grade mixtures were used. These mixtures were prepared gravimetrically and are the most accurate grade of gas mixtures commonly available. Table C-6 lists the grades of gases currently available for each span gas.

Sampling Location Flue gas was sampled immediately upstream of the air heater. This ensured that: 1) the flue gas sample was representative of the boiler effluent, 2) that the sample was not biased by the buildup and intermittent discharge of ash from the air preheater, and 3) the results do not reflect the performance of the emission control system. An array of sampling probes was used. This ensured that the composite sample was representative of the total boiler exhaust. The probes could be sampled separately to assess the variations in gas concentrations across the duct.

The sampling port arrangement for the WIPCO field evaluation boiler is shown in Figure C-4. Three ports are used for a 3 x 4 array of probes for the continuous monitoring system. Two additional ports are used for manual sampling and can be used for the Level 1 SASS probe. Note that this sampling location did not meet the requirements of EPA Method 1 which specifies a minimum straight length of 2.0 duct diameters upstream and 0.5 duct diameters downstream from the sampling point. However, this was the best location available. The duct pressure at the sampling location is approximately 6.0 inches H_2O above ambient. To prevent leakage of combustion products when the ports were opened to traverse or remove probes, each port was equipped with the seal/air system shown in Figure C-5. During sampling the port opening is sealed and/or the flow rate of compressed air minimized to avoid diluting the sample or altering the flow streamlines in the duct.

TABLE C-6. CALIBRATION GASES

Gas	Concentration	Percent Full-Scale	Gas	Grade
NO	500 ppm	50	Nitrogen	EPA Protocol
NO	900 ppm	90	Nitrogen	EPA Protocol
SO_2	2500 ppm	50	Air	EPA Protocol
SO_2	4500 ppm	90	Air	Gravimetric (GMPS)
CO	250 ppm	50	Nitrogen	EPA Protocol
CO	450 ppm	90	Nitrogen	EPA Protocol
CO_2	12.5%	50	Nitrogen	EPA Protocol
CO_2	22.5%	90	Nitrogen	EPA Protocol
O_2	5%	50	Nitrogen	EPA Protocol
O_2	9%	90	Nitrogen	EPA Protocol
C_3H_8	25 ppm	50	Nitrogen	Gravimetric (GMPS)
C_3H_8	45 ppm	90	Nitrogen	Gravimetric (GMPS)

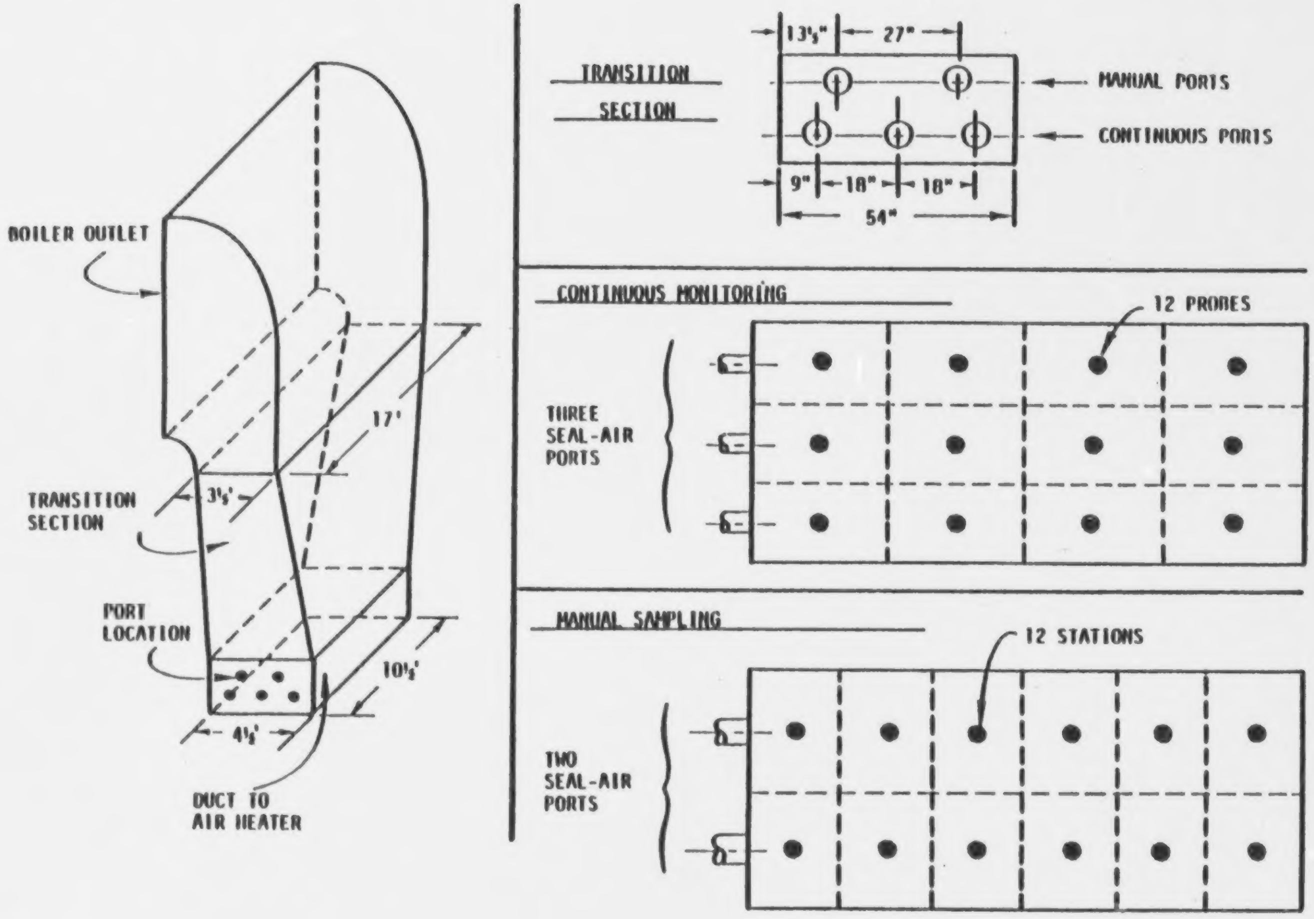


Figure C-4. Sample port arrangement for WIPCO field evaluation boiler.

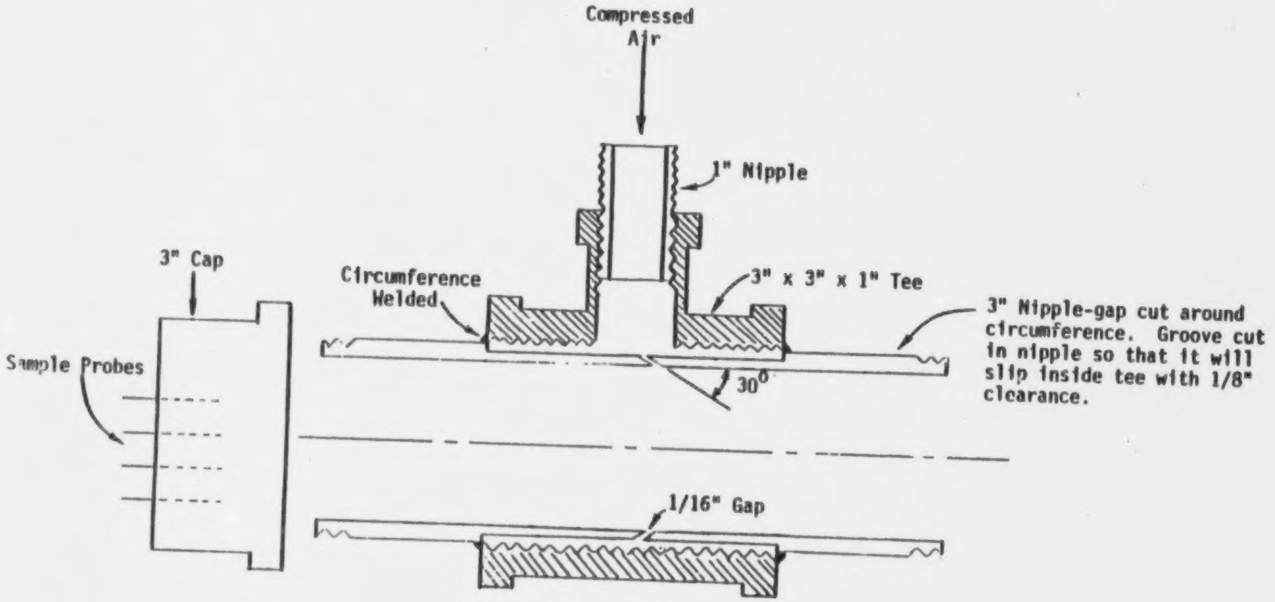

Compressed Air
1" Nipple
3" Cap
Circumference Welded
3" x 3" x 1" Tee
3" Nipple-gap cut around circumference. Groove cut in nipple so that it will slip inside tee with 1/8" clearance.
Sample Probes
30°
1/16" Gap

Figure C-5. Seal air sample port.

Sample Train

Figure C-6 shows the key elements of the sample train design. All materials in contact with the sample upstream of the reactive gas analyzers (NO_x and SO_2) were limited to glass, stainless steel, Teflon and a small amount of Kel-F. These materials have been shown to have negligible effects on the reactive gases under the conditions present in this sample train. The probes are uncooled stainless steel and are equipped with particulate filters on the tips. These filters are sintered stainless steel cylinders 1.0-inch diameter and 6.0 inches long. The nominal pore size is 0.5 micron. Experience with these filters has been satisfactory and the pressure drop across each filter was maintained at an acceptable level by daily backflushing.

The sample lines from each probe were heated to maintain the gas temperature above the dew point. These sample lines entered a temperature-controlled box where the sample flow rates in all probes were balanced and filtered. The temperature of the box was maintained at about 250°F which is above the moisture dew point. The filters were packed with glass wool. The flow rate through each sample line was monitored and controlled by an orifice, differential pressure indicator and metering valve. A common differential pressure indicator was used for all sample lines. Each orifice was calibrated by measuring the differential pressure at the desired sampling rate. Experience has shown that the orifices (which are cut from Teflon discs) can be produced to have essentially the same calibration. Thus, uniform flow through each probe was indicated by the same differential pressure across each orifice. The temperature-controlled box included valves to manifold any combination of probes into the single sample line. Also, there was provision for dry filtered compressed air to back-purge the system.

The sample line exiting the temperature-controlled box was heated to 250°F and conveyed the sample to the instruments which were located in a temperature controlled environment (air-conditioned trailer). A teflon-lined sample pump provided the pressure and was operated at the maximum possible flow rate to achieve minimum sample line residence time. An insulated sample

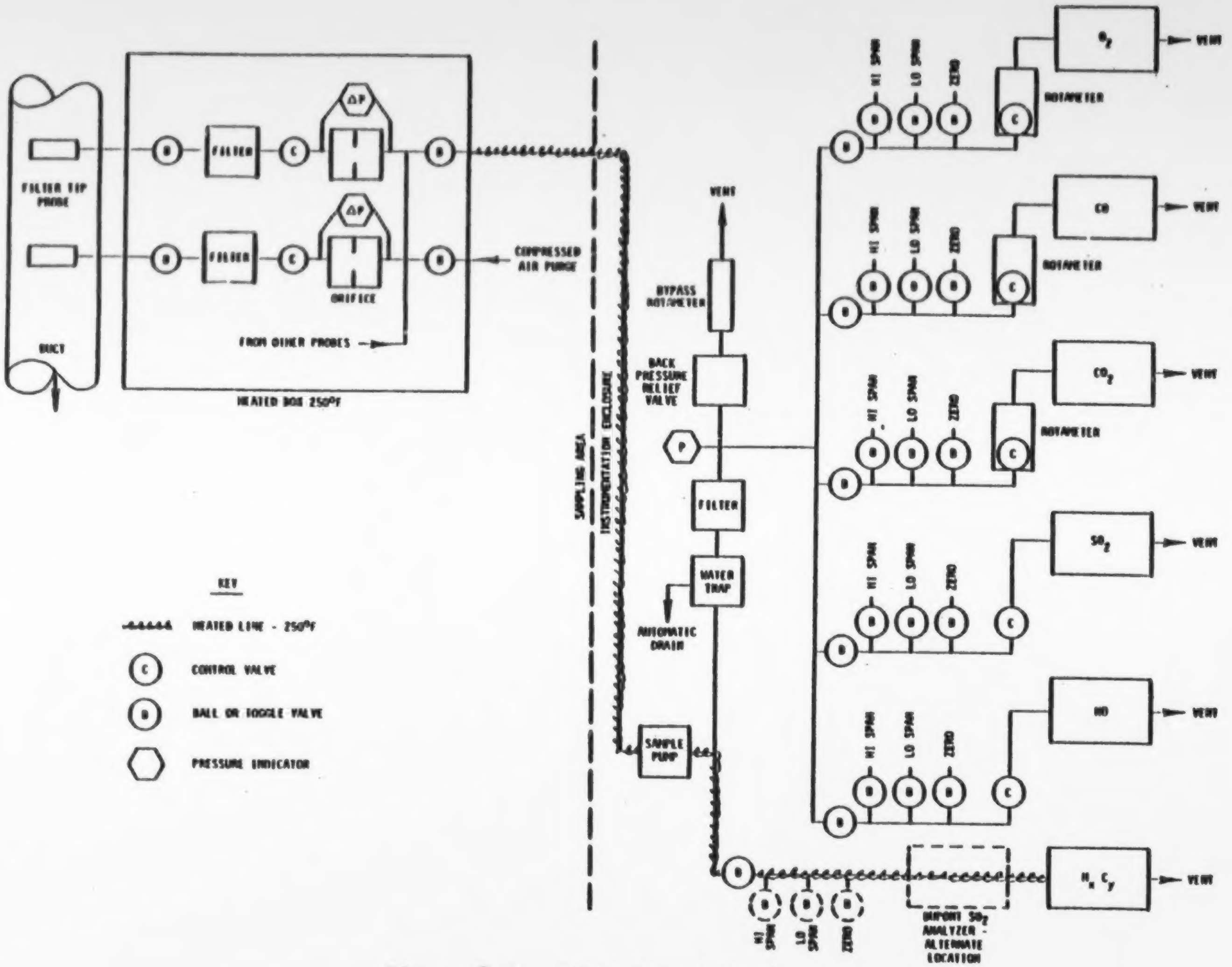


Figure C-6. Field sample train.

line supplied the hydrocarbon analyzer directly. The remainder of the sample was dried and filtered and then distributed to the analyzers. Excess sample (which was the majority of the flow rate) was vented through a back pressure relief valve. The sample flow rate was measured by a bypass rotameter and smaller rotameters connected to each instrument. The TECO analyzers (SO_2 and NO_x) had internal flow meters. The zero and span gas connections were arranged so that each instrument could be spanned separately.

The signals indicating the gas concentrations on each instrument were supplied to a strip-chart recorder. A data acquisition system was used also to facilitate the evaluation of calibration data and for data reduction during the extended test periods.

C.2.2 Quality Control/Assurance

The key element in the Quality Control Plan is a verification that the continuous monitoring system conforms to EPA Performance Specifications 2 and 3. This verification was several times during the test program. The Performance Specifications are for NO_x, SO_2, CO_2 and O_2 monitors which are used to demonstrate compliance with New Source Performance Standards. The design of the continuous monitoring system for the field test met the construction requirements of the Performance Specifications. The operational specifications are listed in C-7. A zero gas and two span gases are required for each instrument. The span gases are 50 and 90 percent of the span range and must be certified to be accurate. The certification involves either preparation according to EPA Protocol No. 1 (which involves comparison against NBS standards) or a specified calibration procedure involving comparison against EPA Manual methods.

Performance of the monitoring system is verified in a two-week tests. During the first week (conditioning period), the system must operate with no unscheduled maintenance, repairs or adjustments. During the second week (operational period), the system is tested for compliance with the remaining specifications listed in Table C-7. This includes zero drift, calibration drift and relative accuracy. In the relative accuracy test, the responses of

TABLE C-7. EPA PERFORMANCE SPECIFICATIONS FOR CONTINUOUS ANALYZERS

Test	NO_x and SO_2	O_2 and CO_2
Span Gas	EPA Protocol	Same
Conditioning Period	≥168 hours	Same
Operational Period	≥168 hours	Same
Calibration Error	≤5% of each mid-level and high-level calibration value	Same
Response Time	≤15 minutes	Same
Zero Drift (2 hours)	≤2% of span	≤0.4% CO_2 or O_2
Zero Drift (24 hours)	≤2% of span	≤0.5% CO_2 or O_2
Calibration Drift (2 hours)	≤2% of span	≤0.4% CO_2 or O_2
Calibration Drift (24 hours)	≤2% of span	≤0.5% CO_2 or O_2
Relative Accuracy	≤20% of the mean value of reference method(s) test data in terms of emission standard or 10 percent of the applicable standard, whichever is greater	Same

the continuous monitors are compared with EPA Manual measurements. EPA Method 6 is used for SO_2, EPA Method 7 is used for NO_x and EPA Method 3 is used for CO_2 and O_2.

The EPA Performance Specifications include NO_x, SO_2, O_2 and CO_2 monitors, but do not cover CO and hydrocarbon monitors since these pollutants are not currently regulated by New Source Performance Standards. To provide some assurance that CO and hydrocarbons were monitored accurately, the monitors for these species were tested in the same manner as the others. However, since there were no appropriate EPA Manual methods for these species, the relative accuracy tests were not conducted.

The key element in data quality assurance was a review of test procedures, equipment, documentation, and measurement accuracy by an independent third party. The measurement system at the initial field evaluation boiler was subjected to on-site qualitative systems audits and quantitative performance audits by RTI, an independent auditor selected by EPA.

A system audit provides an assessment of facilities and equipment, adequacy of test procedures selected, conformance to test procedures, maintenance and calibration procedures selected, and documentation. The performance audit assesses the accuracy of data using independent measurement techniques, primarily involving the analysis of reference samples. Table C-8 summarizes the audit procedures of all measurements except the EPA Level 1 environmental conducted at WIPCO. The results of the audit were satisfactory except for some minor problems which were corrected.

TABLE C-8. SUMMARY OF TEST METHODS AND AUDIT PROCEDURES

TEST METHOD	SYSTEMS AUDIT PROCEDURE	PERFORMANCE AUDIT PROCEDURE
Continuous Monitoring Instrumentation	Review of facilities and equipment. Review of calibration and maintenance procedures. System documentation.	Analysis of standard compressed gases introduced at sampling probes. Individual probe flow rates checked against NBS.
EPA Reference Methods 2, 3, 4, 5, 6, 7, 8	Observation of sample collection and analysis. Review of data forms, calibration, and documentation. Check of equipment for conformance to EPA specifications.	Method 3: Analysis of standard gases. Method 5: Check of gas meter accuracy against calibration orifice. Methods 6 and 8: Analysis of standard sulfuric acid solutions. Method 7: Analysis of standard NO_2 samples in absorbing solutions.
Controlled Condensation for SO_3	Observation of sample collection. Review of data forms, test procedure, equipment, and documentation.	
In-Stack Cascade Impactor for Particle Size	Observation of loading of impactor with substrates, sample collection, and unloading of impactor.	

APPENDIX D
CALIBRATION OF BURNER INTERNAL AIR FLOW METERS

The DMB installation at WIPCO required that all of the combustion air (except the primary) be supplied by a common windbox. To determine the burner zone stoichiometry and the balance of air flow supplied to the four burners and thirteen tertiary air ports, it was necessary to measure the air flow rates through each burner passage. This was achieved by measuring the pressure drops across restrictions in each burner passage and relating these pressure drops to air flow rates based on correlations developed during air flow tests. Thus, the restrictions functioned as "internal flow meters". This Appendix discusses the design, operation and calibration of these internal flow meters.

Since the internal flow meters were integrated with a commercial burner design, it was not possible to use standard geometry for the flow rate instrumentation. To develop accurate correlations between pressure drops and flow rates it was necessary to calibrate each flow meter separately. These calibrations were conducted at full scale and the procedures are discussed in the following subsection.

Internal flow meters were utilized in the prototype burner tests as well as the WIPCO installation. In the prototype burner tests, a common windbox supplied the single DMB and the four tertiary air ports. The designs of the internal flow meters on the prototype DMB were identical to those on the DMBs installed at WIPCO. However, a preliminary tertiary air port control/flow meter was utilized. The design and calibration of the prototype burner flow meters are presented in subsection D.2.

For the WIPCO installation, the tertiary air port array was more complex than for the prototype burner. Also, commercial service required consideration of long term performance. For these reasons, the preliminary tertiary air port control/flow meters utilized for the prototype burner tests were considered unacceptable for the WIPCO installation. Modified designs were employed. The designs and calibrations are presented in subsection D.3.

Finally, subsection D.4 discusses the control of burner operation and the use of the calibrations during the prototype and field DMB tests. Recommendations for improved burner flow rate measurement and control are included.

D.1 Calibration Methods and Procedures

The relationship between the airflow rate and the pressure drop across a flow restriction can be expressed in the following form:

$$Q = K_1 \left(\frac{P_i}{T}\right)^{1/2} \tag{1}$$

where:

Q = mass flow rate of air through the burner passage (SCFM)

P_i = pressure drop across the flow measurement device (in. H_2O)

T = absolute air temperature (^oR)

K_1 = a calibration constant which may depend on Reynolds Number, windbox pressure, the adjustments of adjacent flow control devices and effective open area of the flow measurement device.

For the high Reynolds Number flow conditions at which the measurement devices typically operate, Reynolds Number effects are usually small and can be neglected. Windbox pressure is usually only a few inches of H_2O greater than ambient and thus, changes in windbox pressure encountered in normal operation are small compared to the absolute pressure and have a negligible effect on a calibration by altering the airflow in the vicinity of the pressure taps. This effect must be empirically evaluated. The relationship between K_1 and open area is approximately linear and must be calibrated.

The relationship between the airflow rate through a burner passage and windbox-to-furnace pressure differential may be expressed in a similar manner:

$$Q = K_2 \left(\frac{P_{wb}}{T}\right)^{1/2} \qquad (2)$$

where the new symbols are defined as follows:

P_{wb} = windbox-to-furnace pressure differential (in. H_2O)
K_2 = a calibration constant which depends on Reynolds Number and the adjustment of the airflow control devices

It should be noted that the presence of a flame in the furnace may alter the effective P_{wb} for some or all of the burner passages. Thus, cold flow calibrations may be slightly different than the actual fired performance.

The relationships between Q and P_i or P_{wb} were evaluated by physically blocking all burner passages which were not in use and measuring the airflow rate into the windbox with a calibrated venturi flow meter. For selected tests, the air flow rates exiting the burner passages were measured by pitot tube traverses to ensure that leakage through the other burner passages could be neglected. Pressure drops were measured with manometers and Magnehelic differential pressure gauges. Temperatures were measured with thermocouples.

The effects of register position on swirl in the outer secondary air passage were measured with a five-hole probe. The magnitude and direction indicated by the probe were calibrated in a straight duct where the flow direction was known and the velocity was determined with a pitot tube.

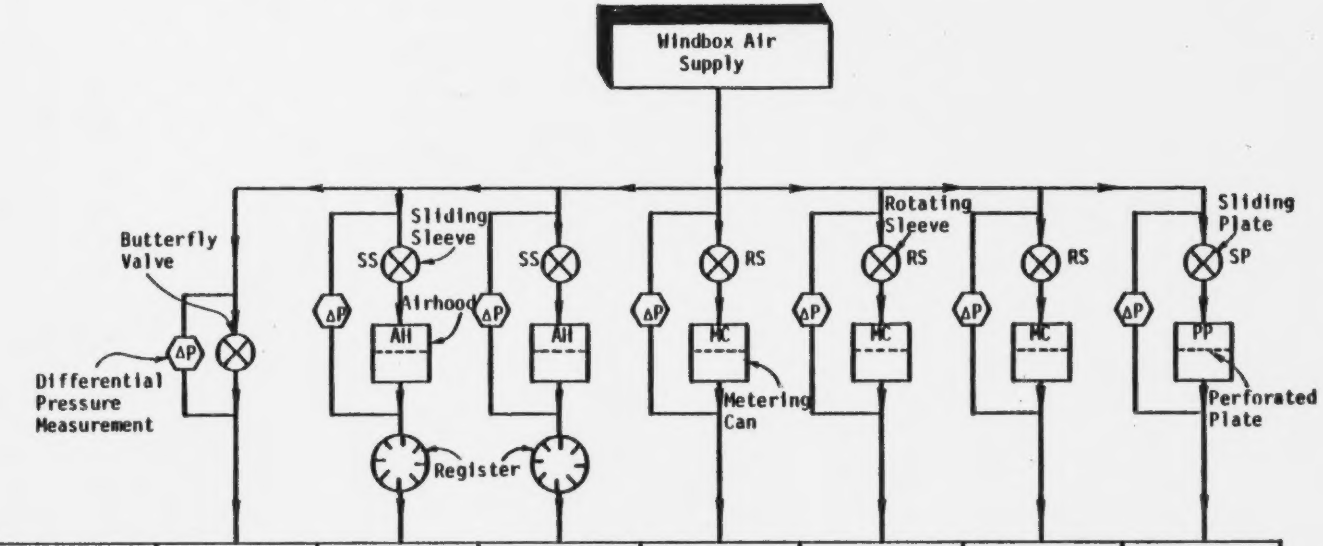
D.2 Calibrations of Prototype DMB Flowmeters

The prototype DMBs were supplied with combustion air from two sources. The coal nozzle was supplied with air (and coal) from the pulverizer. The primary air flow rate was measured and controlled as part of the pulverizer system. The other burner passages were supplied with air from a common windbox. Figure D-1 shows the air flow control and measurement devices which allowed the distribution of air among the burner passages to be adjusted and monitored. The central burner passage (core) was connected to the windbox with a six-inch pipe equipped with a butterfly valve for flow control. The core airflow rate was monitored by measuring the pressure drop across the valve. The relationship between airflow rate and pressure drop depended on the specific pressure tap locations, as well as valve position. Calibration was required.

The airflow measurement and control devices on each secondary passage included a sliding sleeve, a perforated plate (air hood) and a register. The primary function of the sliding sleeve was to vary the effective open area of the air hood and thus, vary the airflow rate. The primary function of the register was to provide swirl. However, the register is a flow restriction and affects the airflow rate as well. For example, when the burner is removed from service, the register is closed to shut-off the airflow. The primary function of the air hood is to provide a pressure drop which can be used to monitor airflow rate. The relationship between pressure drop and airflow rate depends on sleeve position and, to a lesser extent, upon register position.

The four tertiary ports used in the prototype DMB tests were equipped with perforated plates and poppet valves. The components were arranged so that the perforated plate open areas were constant, independent of poppet valve positions. Thus, the pressure drops across the perforated plates provided direct indications of flowrate and only a single calibration was required for each.

The following three subsections present the calibrations of the core, inner secondary and outer secondary. Since these same components were used for the DMBs installed at WIPCO, these correlations were used during the field tests. Subsection D.2.4 presents the calibrations of the tertiary air port flowmeters. Since alternate designs were used at WIPCO, these calibrations apply to the prototype burner tests only.



Burner Passage	Core	Inner Secondary	Outer Secondary	Top Tertiary Ports (4)	Outboard (4) Tertiary Ports	Center (1) Tertiary Ports	Bottom (4) Tertiary Ports
Separate Control and Measurement Systems	4	4	4	4	4	1	1
Flow Control Element	Butterfly Valve	Sliding Sleeve (SS)	Sliding Sleeve (SS)	Rotating Sleeve (RS)	Rotating Sleeve (RS)	Rotating Sleeve (RS)	Sliding Plate (SP)
Flow Measurement Element	Butterfly Valve	Air Hood (AH)	Air Hood (AH)	Metering Can (MC)	Metering Can (MC)	Metering Can (MC)	Perforated Plate (PP)

Figure D-1. Prototype burner airflow rate measurement and control.

D.2.1 Core

The butterfly valve, which is used as the flow measurement element for the core, is the major restriction between the windbox and furnace. As expected, P_i and P_{wb} were found to be approximately equal for all test conditions. Figure D-2 shows the relationship between the flowrate, pressure drop and temperature for several butterfly valve positions. Equations 1 and 2 are expressed by straight lines on the coordinates of Figure D-2. These results show that the core air valve is an effective airflow rate control. Adjusting the valve from fully closed to fully open (at constant P_i/T) varies the airflow rate by a factor of 3.4. Least squares fits through the calibration data give the relationships shown in Table D-1. The calibration constants for these relationships are shown as a function of the valve position in Figure D-3. The relationship is approximately linear from full open to 60 degrees from full open. Table D-1 also shows the final correlation which is valid over the linear range. The standard deviation for this correlation is 27 percent. This is relatively poor accuracy. However, the core airflow rate is small compared to the other burner passages supplying the throat. Thus, the poor accuracy is not a significant factor in the determination of burner zone stoichiometry or burner balance.

It should be noted that an alternate air flow meter design for the core was evaluated during the Intervane burner tests. A standard venturi was installed between the windbox and butterfly valve. The increased flow restriction caused by the venturi altered the combustion performance of the burner and thus the less accurate valve pressure flow meter was used for the DMBs.

D.2.2 Outer Secondary

The air control systems for the secondaries each have three flow restrictions: sleeve, air hood and register. the pressure drop across the sleeve and air hood is used to monitor flow rate. This pressure drop is always less than the total windbox pressure drop due to the pressure drop across the register. Figure D-4 shows the relationship between flow rate,

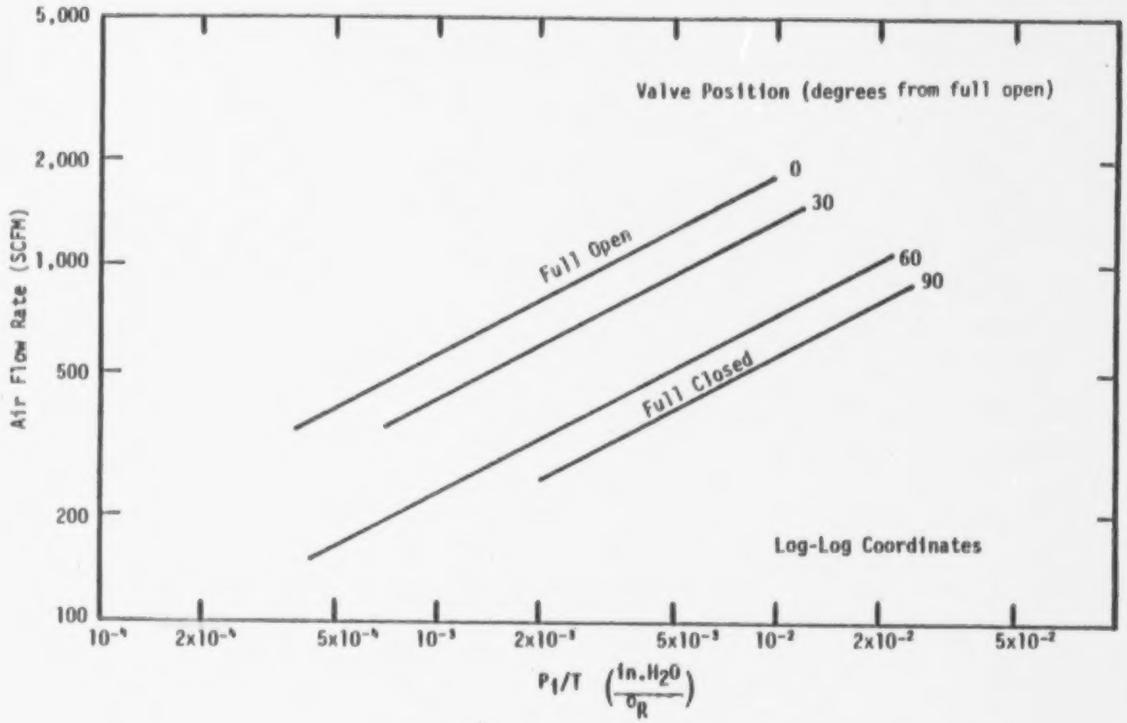


Figure D-2. Core air valve calibrations.

TABLE D-1. AIRFLOW RATE CORRELATIONS - CORE

Core Valve Position	EQUATION	DEVIATION
0 Degrees	$Q = 18284\ (\Delta P/T)^{1/2}$	± 9.0%
30 Degrees	$Q = 13400\ (\Delta P/T)^{1/2}$	± 12.7%
60 Degrees	$Q = 7357\ (\Delta P/T)^{1/2}$	± 26.7%
90 Degrees	$Q = 5647\ (\Delta P/T)^{1/2}$	± 18.4%
	COMBINED RESULTS	
0 - 60 Degrees	$Q = (18475 - 182\ P_V)\ (\Delta P/T)^{1/2}$	± 27%

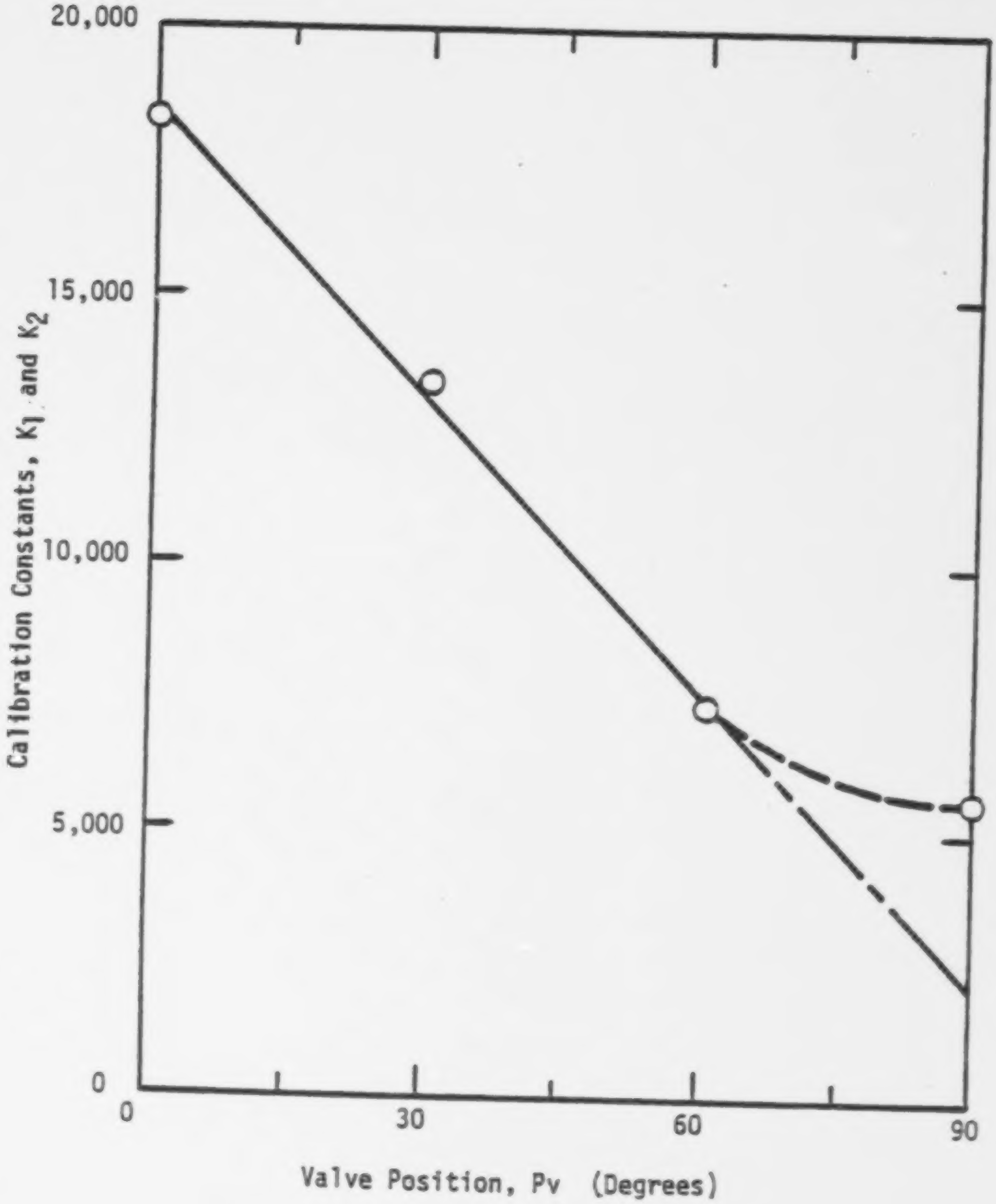


Figure D-3. Calibration Constants For Core Air Valve.

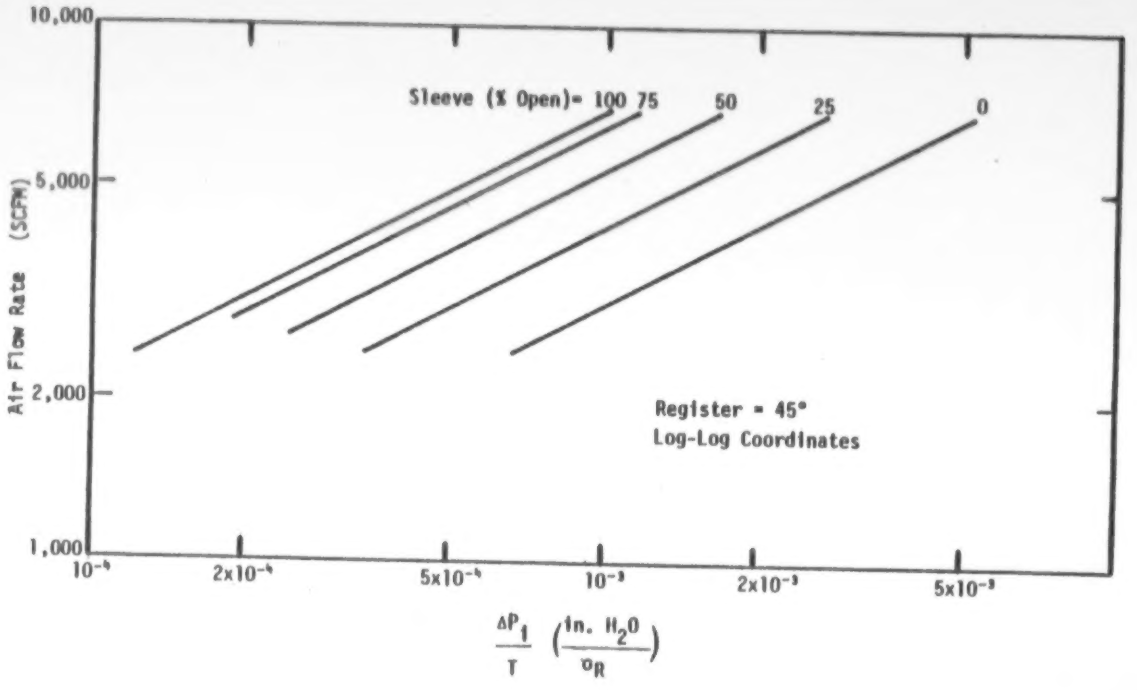


Figure D-4. Outer secondary calibration.

pressure drop across the outer secondary sleeve and air hood, and temperature for several sleeve positions. The change in airflow rate as sleeve position is adjusted is approximately linear from zero to 75 percent open. However, opening the sleeve to 100 percent results in a smaller increase in airflow rate. This is due to the clearance between the sleeve and air hood. When the sleeve is nearly fully open, the flow restriction through the clearance is comparable to the flow restriction through the portion of the air hood covered by the sleeve. The clearance also affects the calibration when the sleeve is fully closed. In this case, all of the airflow passes through the clearance. Thus, the calibration of this device is sensitive to the clearance especially in the closed or nearly closed position.

The calibration in Figure D-4 was conducted with the register at 45 degrees. Similar calibrations were conducted over a range of register positions with the sleeve fully open. Figure D-5 shows the calibration constant determined from these tests as a function of register position. The calibration constant is invariant within the standard deviation range of the correlations over the normal range of register positions (30 degrees to 60 degrees). However, it is significantly higher for positions outside this range.

Table D-2 shows the outer secondary correlations for each sleeve position and an average correlation for all sleeve positions. The standard deviation for the average correlation is 10 percent which is considerably less than for the core air valve.

The windbox pressure drop was correlated with the airflow rate over a range of sleeve and register positions also. Due to the clearance between the sleeve and air hood (discussed above), the sleeve position had a minimal effect compared to register position. The correlation is as follows:

$$Q = (201601-1966\ P_r)\left(\frac{P_{wb}}{T}\right)^{1/2} \qquad (3)$$

where:

P_r = position of register (degrees from fully open)

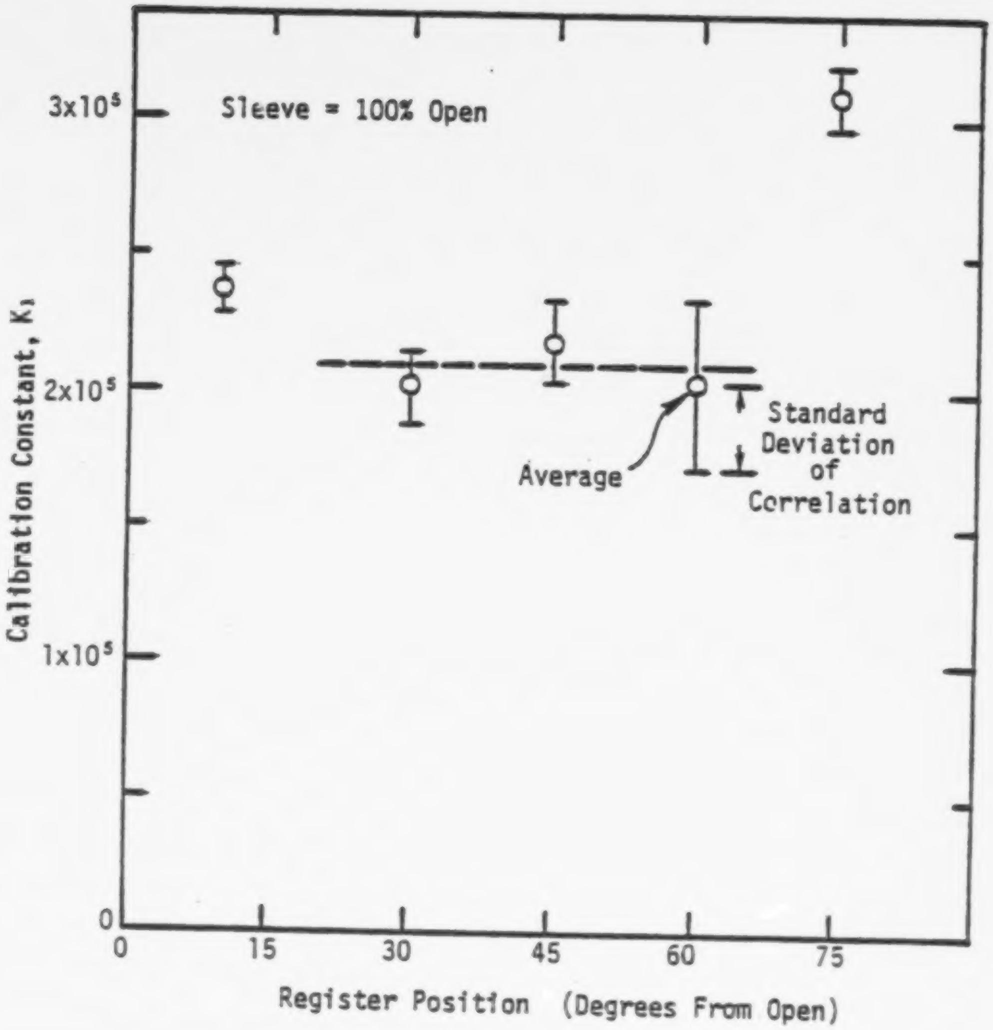


Figure D-5. Effect of Outer Register on Calibration Constant, K_1.

TABLE D-2. AIRFLOW RATE CORRELATIONS - OUTER SECONDARY

Register Range 30-60° Open

Sleeve Position	EQUATION	DEVIATION
100% Open	$Q = 218726\ (\Delta P_i/T)^{1/2}$	± 6.9%
75% Open	$Q = 202582\ (\Delta P_i/T)^{1/2}$	± 0.6%
50% Open	$Q = 167958\ (\Delta P_i/T)^{1/2}$	± 7.0%
25% Open	$Q = 131795\ (\Delta P_i/T)^{1/2}$	± 2.4%
0% Open	$Q = 95653\ (\Delta P_i/T)^{1/2}$	± 7.6%
COMBINED RESULTS		
0 - 100% Open	$Q = (95955 + 1428\ P_s)\ (\Delta P_i/T)^{1/2}$	± 10%

This relationship is valid over the normal range of register positions (30 to 60 degrees) and illustrates the throttling effect of closing the register.

The register provides swirl also. The swirl angle in the burner throat was measured with a five-hole probe. Figure D-6 shows the swirl as a function of register position. The data points were measured by traversing the probe on a horizontal line across the throat. The theoretical swirl angle was calculated assuming that the register channels all air in the direction of the vanes and conservation of angular momentum. This relationship is shown in Figure D-6 also. At low register settings (register vanes almost radial) the measured swirl angle is somewhat greater than the theoretical relationship. This is probably due to experimental error including uncertainty in register position and the traversing of the five-hole probe along a single line. At higher register settings the rate of increase of swirl angle with register position tapers off. This is probably due to leakage around the register vanes.

The results in Figure D-6 show that over the normal register operating range (30° to 60°) the register position has minimal effects on swirl angle. Thus, the primary effect of register adjustment in this range is flow restriction.

D.2.3 Inner Secondary

The inner secondary was calibrated in the same manner as the outer secondary except that no swirl angle measurements was made. Figure D-7 shows the relationship between pressure drop across the sleeve and air hood, air flow rate, and temperature for several sleeve positions. Due to mechanical interference, the sleeve could not be fully closed. As with the outer secondary, the clearance between the sleeve and air hood affected the calibration for sleeve positions greater than 75 percent open. The test results show essentially the same flow rate for sleeve positions of 75 and 100 percent open. The effect of register position is shown in Figure D-8. This calibration is similar to that for the outer secondary. The calibration

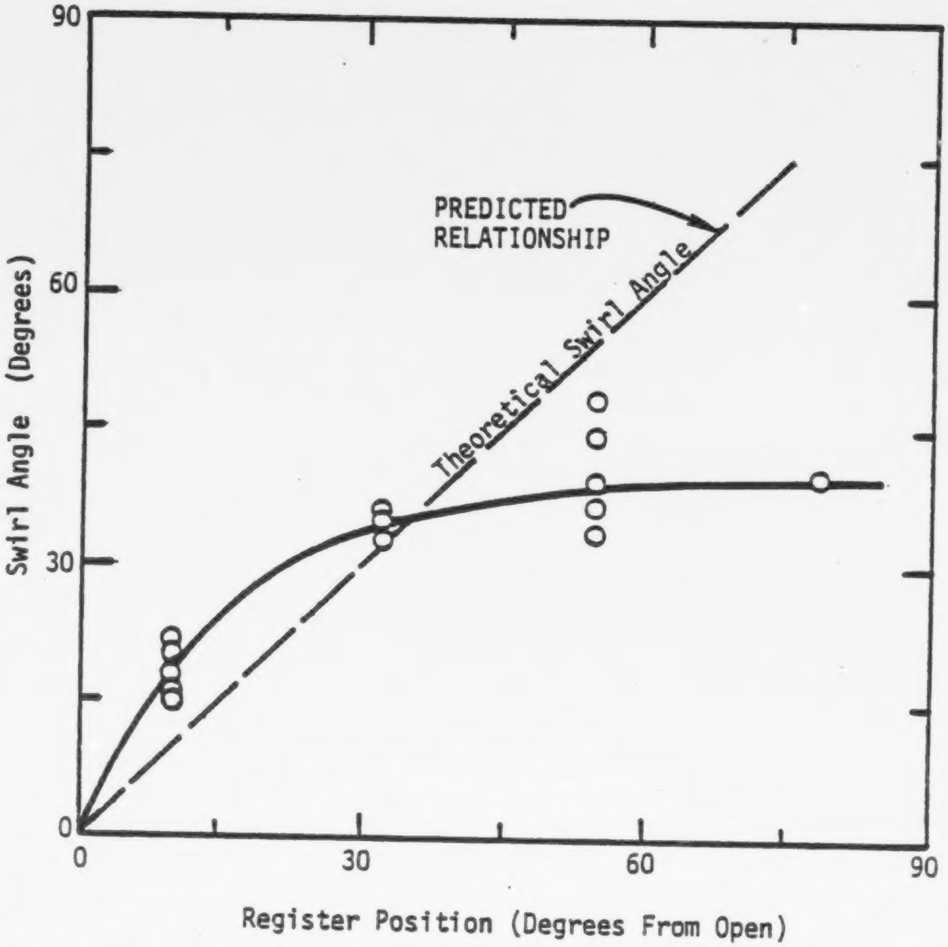


Figure D-6. Swirl Angle in Outer Secondary.

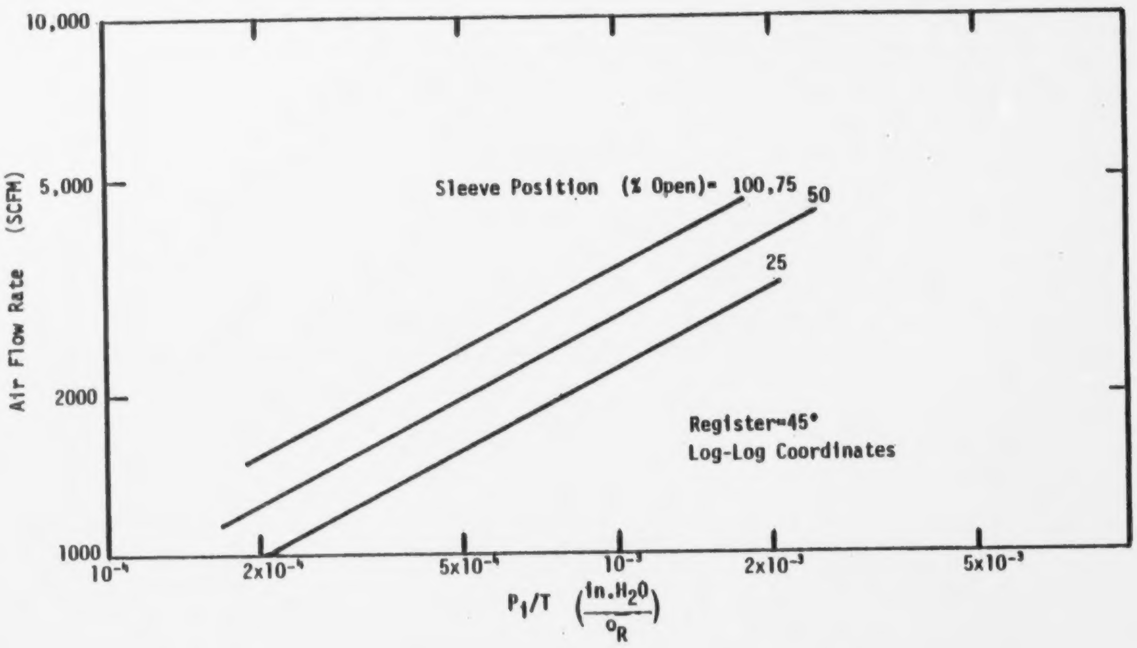


Figure D-7. Inner secondary calibration.

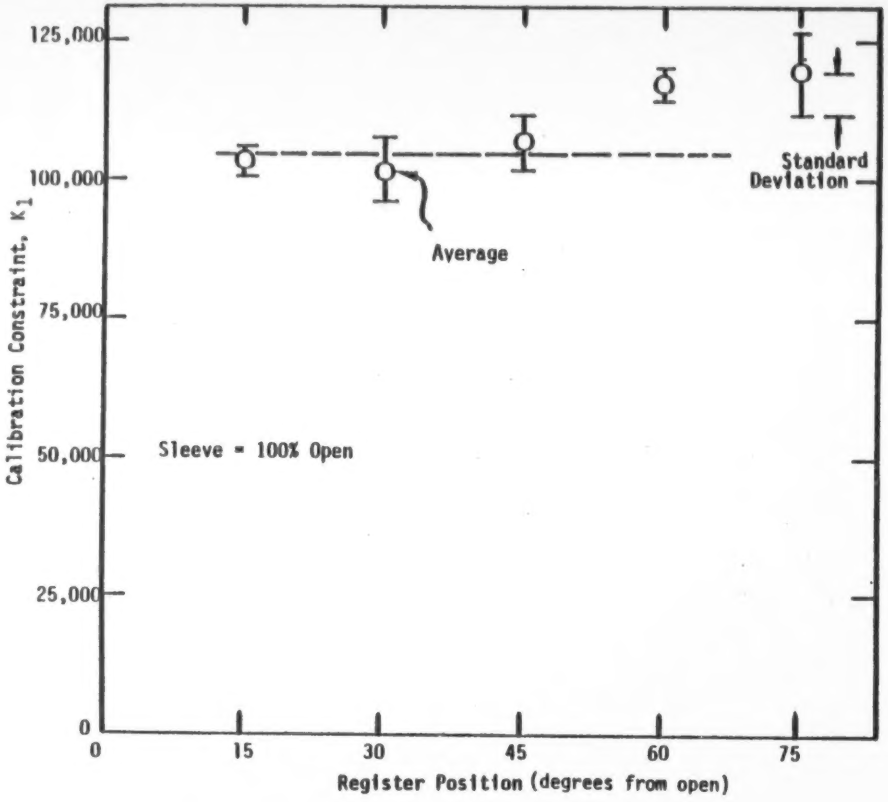


Figure D-8. Effect of inner register on calibration constant, K_1.

constant is unaffected by register position except for nearly closed positions where it is higher.

Table D-3 shows the inner secondary correlations for each sleeve position and an average correlation for all sleeve positions. The standard deviation for the average correlation is 10 percent, the same as the outer secondary. The windbox pressure drop was correlated with register and sleeve positions with the following result:

$$Q = (0.64 + 0.0036\,P_s)\,(931168\text{-}515\,P_r)\left(\frac{P_{wb}}{T}\right)^{1/2} \qquad (4)$$

where:

P_s = position of the sleeve (percent open)

Comparison of the correlations for the inner and outer secondaries (Tables D-2 and D-3, and Equations 3 and 4) shows that for similar settings and pressure drops, the air flow rate through the outer secondary is approximately twice as great as through the inner secondary. Thus, at the nominal burner design point, the indicated pressure signals on both secondaries are about equal.

D.2.4 Tertiary Ports

The effective open area of the perforated plate used for airflow rate measurement on each tertiary port is independent of control valve position. Thus, a single calibration should be sufficient to fully characterize operation. To verify this on tertiary port assembly was calibrated several control valve positions. The calibrations were found to be constant, independent of control valve position, within experimental error. In addition, the calibrations were found to be independent of the following parameters:

- Location within the windbox
- Manufacturing tolerances

TABLE D-3. AIRFLOW RATE CORRELATIONS - INNER SECONDARY

Sleeve Position	EQUATION	DEVIATION
100% Open	$Q = 107374\ (\Delta P_i/T)^{1/2}$	± 4.7%
75% Open	$Q = 107439\ (\Delta P_i/T)^{1/2}$	± 1.1%
50% Open	$Q = 87821\ (\Delta P_i/T)^{1/2}$	± 7.7%
25% Open	$Q = 69904\ (\Delta P_i/T)^{1/2}$	± 6.4%
COMBINED RESULTS		
25-75% Open	$Q = (50853 + 751\ P_s)\ (\Delta P_i/T)^{1/2}$	± 10%

- Pressure tap locations
- Tertiary port exit diameter
- Air temperature
- Windbox pressure

Figure D-9 shows the average calibration and data from the four tertiary port assemblies.

The position of the control valve determine the overall flow restriction in the tertiary air passage. Consequently, the relationship between P_{wb}, Q and T depends on the control valve position, P_v. This is illustrated in Figure D-10 where the flow rate through one tertiary port is plotted against control valve position for several values of P_{wb}. Note that for constant P_{wb}, the airflow rate is related to control valve position approximately linearly. A crossplot of these data (Figure D-11) shows the expected relationship between airflow rate and P_{wb}/T for constant control valve positions. The correlations for each control valve position and the overall correlations are shown in Table D-4.

The calibrations discussed above are summarized in Table D-5. These relationships were used to determine the burner settings necessary to establish specific flow rates through each burner passage and to evaluate the flow rates from the indicated pressure drops across the flow measurement devices during the tests of the initial prototype DMB and prototype DMB with Foster Wheeler parameters. The final prototype DMB was tested with independent airflow supply to the tertiary air ports.

D.3 Calibration of WIPCO Tertiary Air Control Devices

Four types of control devices were used on the tertiary air ports as shown schematically in Figure D-12. This figure shows the windbox as an open area with registers, coal nozzles, trusses, and buckstays deleted for simplicity. The top, outboard and center ports were controlled by three sizes of cylindrical control valves. Each valve has two parts: a stationary inner cylinder with four perforated plates in the circumference and a

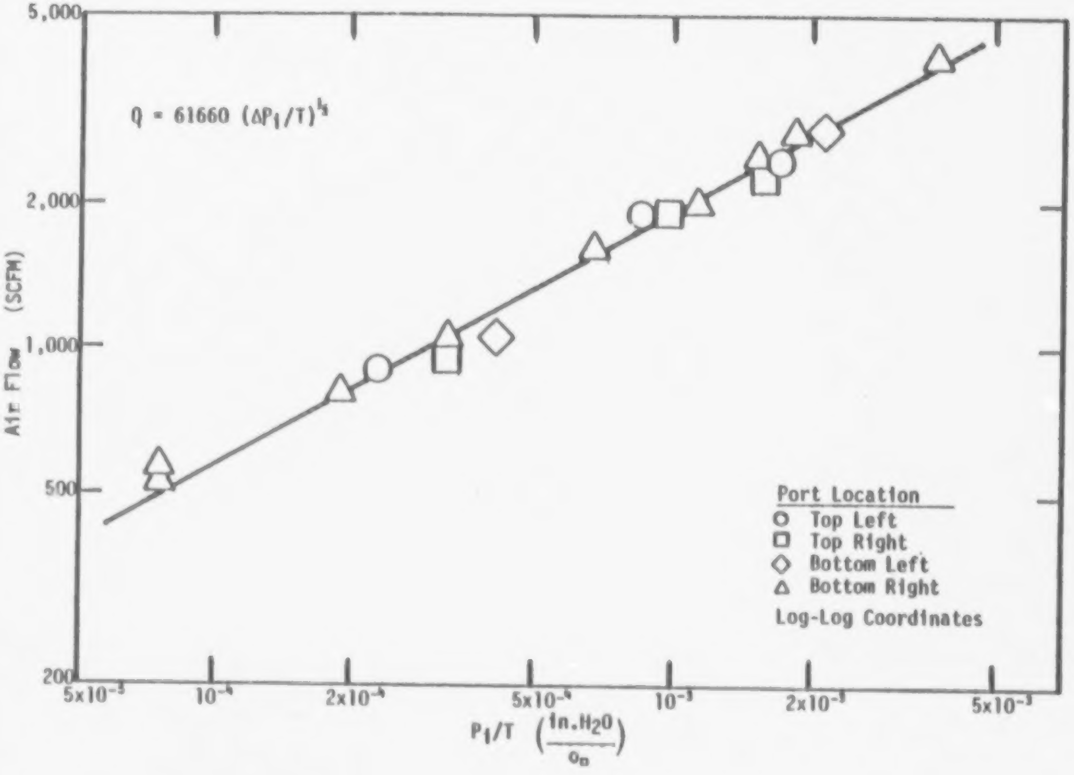


Figure D-9. Prototype DMB tertiary port calibration.

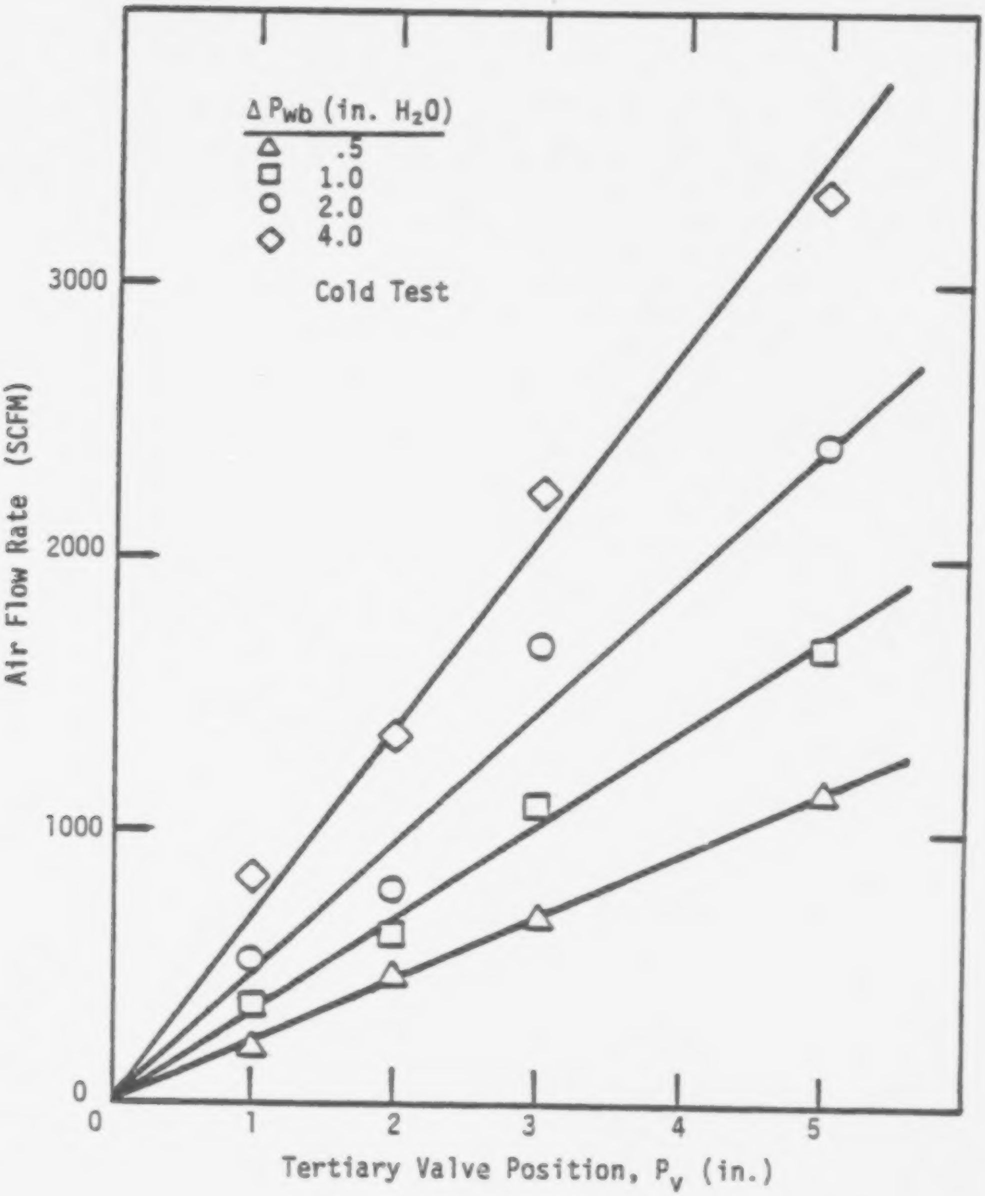


Figure D-10. Effect Of Control Valve Position On Air Flow Rate Through a Prototype DMB Tertiary Port.

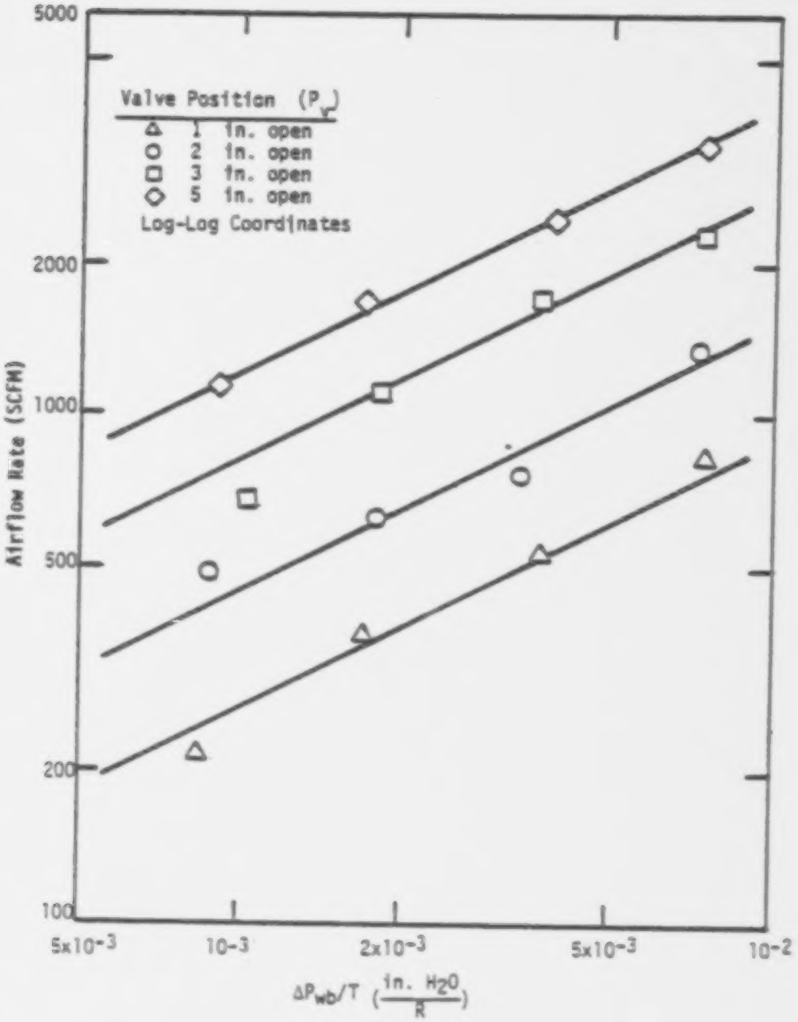


Figure D-11. Effect of windbox pressure differential on airflow rate through a prototype DMB tertiary port.

TABLE D-4. AIRFLOW RATE CORRELATIONS - PROTOTYPE DMB TERTIARY PORT

Valve Position	EQUATION	DEVIATION
1 in. Open	$Q = 8668\ (\Delta P_{wb}/T)^{1/2}$	± 9.5%
2 in. Open	$Q = 15095\ (\ P_{wb}/T)^{1/2}$	± 12.5%
3 in. Open	$Q = 26263\ (\ P_{wb}/T)^{1/2}$	± 10.7%
5 in. Open	$Q = 38635\ (\ P_{wb}/T)^{1/2}$	± 3.0%
COMBINED RESULTS		
2-5 in. Open	$Q = (7609\ P_v + 1300)\ (\Delta P_{wb}/T)^{1/2}$	± 15%

TABLE D-5. CALIBRATION SUMMARY

BURNER PASSAGE	$Q = (\quad)(\frac{\Delta P_i}{T})^{1/2}$	$Q = (\quad)(\frac{\Delta P_{wb}}{T})^{1/2}$	UNITS
CORE	$18500 - 182\ P_v$	$18500 - 182\ P_v$	P_v = Degrees from Full Open
OUTER SECONDARY	$96000 + 1430\ P_s$	$202{,}000 - 1970\ P_r$	P_r = Degrees from Full Open
INNER SECONDARY	$509 + 751\ P_s$	$(0.64+0.0036\ P_s)$ $(93200-515\ P_r)$	P_r = Degrees from Full Open P_s = Percent Open
TERTIARY	60700	$7610\ P_v + 1300$	P_v = Inches Open

Note

Q = SCFM

ΔP_{wb} = in. H_2O

ΔP_i = in H_2O

T = °R

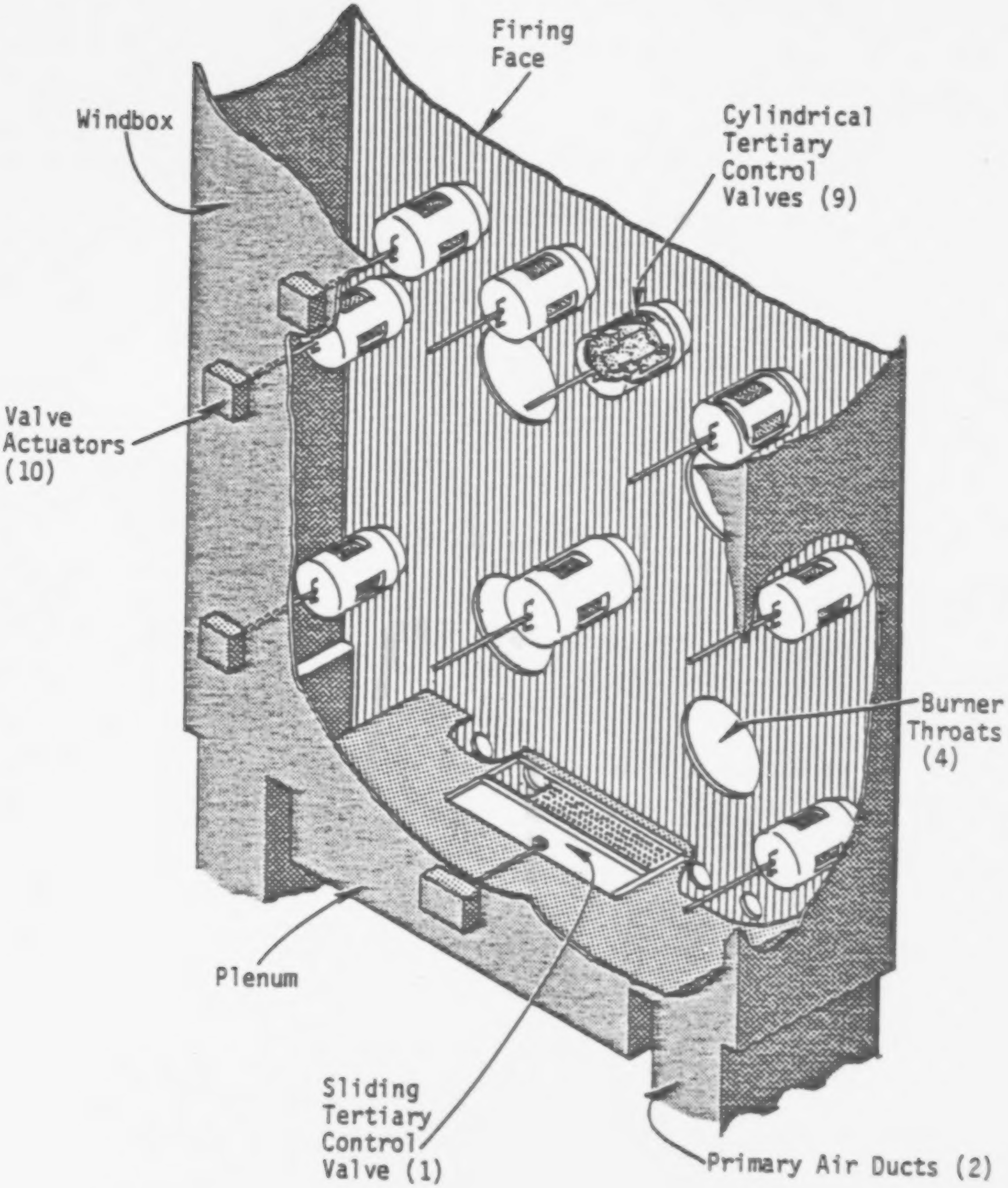
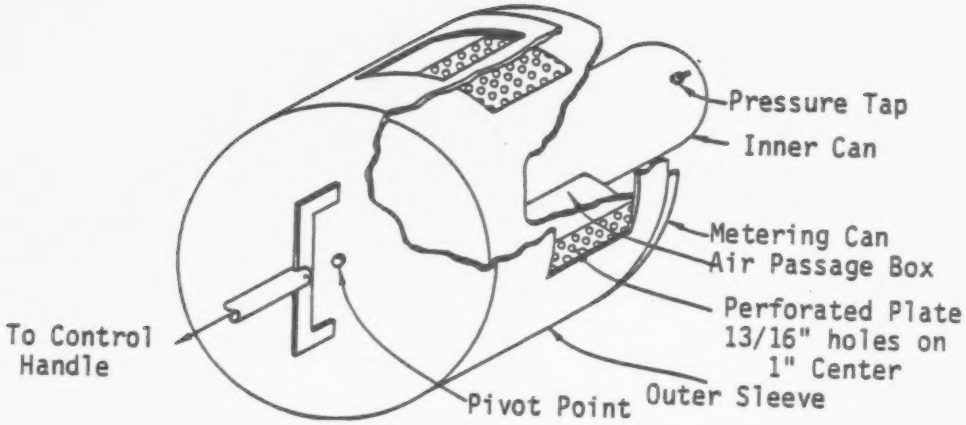


Figure D-12. Tertiary air ports for WIPCO DMBs.

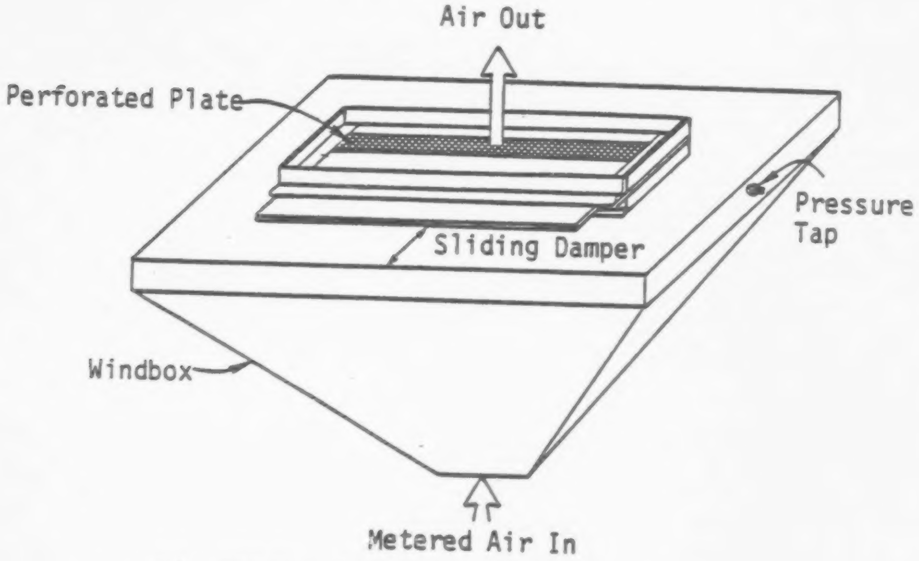
rotating inner cylinder with slots matching the perforated plate locations. Rotating the outer cylinder changed the alignment between the slots and perforated plates and varied the effective open area. The pressure drops were measured across both elements. The bottom four tertiary air ports were supplied with air from a separate plenum below the windbox. The airflow rate into the plenum was controlled by a sliding plate which varied the open area of a stationary perforated plate. The pressure drop was measured between the windbox and plenum.

Full-scale models of the four types of control assemblies were constructed and tested. Their construction is illustrated in Figure D-13. The three sizes of cylindrical control valves were constructed to match the geometry of the field operating units. However, the materials were of lighter gauge, the pivot points were simpler, and the refractory was eliminated and replaced by inner cylinders connected to the metering cans by air passages formed by boxes. The tests were conducted by flowing air, metered by a calibrated venturi, through a cylindrical windbox in which each valve was installed. The angular position of the outer sleeve was measured with a protractor. The air flow rate through the valve was calibrated by measuring the pressure differential across the control valve with a manometer. The sliding damper assembly was calibrated similarly with metered air at several damper positions.

The calibration data for the outboard tertiary air port control valves are shown in Figure D-14. The lines drawn through the data are regression analysis fits to Equation 1. Rotating the sleeve 30^{o} from full-open reduced the air flow rate to the minimum level. Additional rotation to 45^{o} from full-open caused no change in the air flow rate. The regression correlations for each sleeve position are listed in Table D-6. The design of the control valve provides a linear relationship between valve position and effective open area. This can be seen in Figure D-15 where the calibration constants are plotted against valve position. A linear repression analysis results in the overall correlation listed in Table D-6. The flowrates predicted by this correlation based on the $\Delta P/T$ measurements and the measured flowrates are compared in Figure D-16. The standard deviation is 1.4 percent.



a) Cylindrical Tertiary Port Control Valve



b) Sliding Damper Assembly

Figure D-13. Full scale calibration models of tertiary control devices to be used at demonstration boiler.

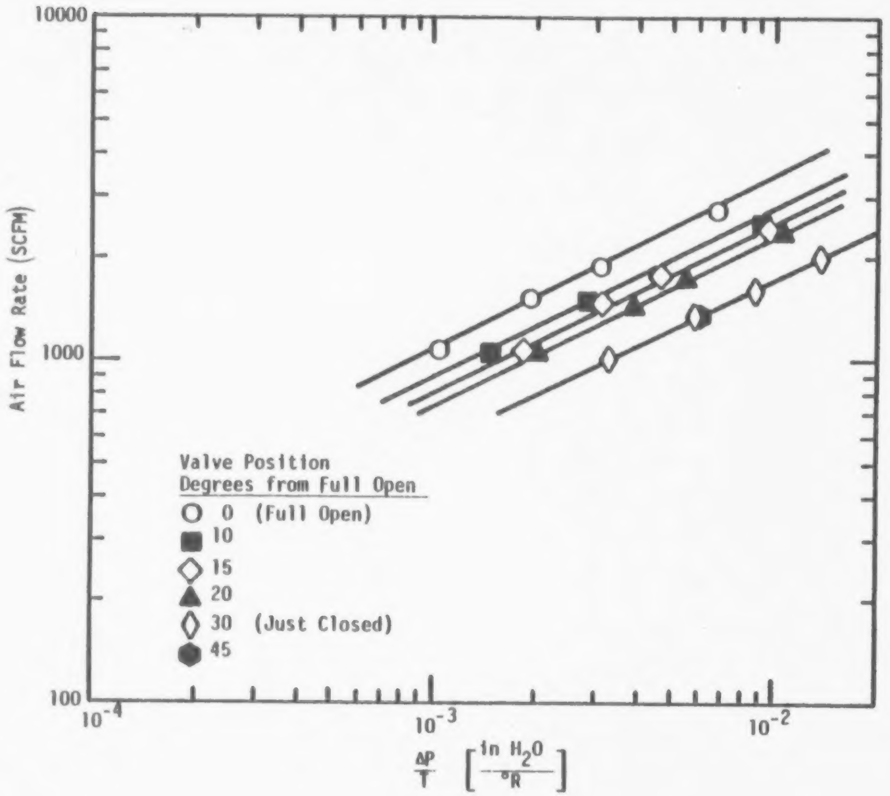


Figure D-14. Outboard tertiary air port control valve calibration data.

TABLE D-6. AIR FLOW RATE CORRELATION - OUTBOARD TERTIARY AIR PORT CONTROL VALVES

Sleeve Position (deg. from Open)	Flow Rate Correlation	Standard Deviation (%)
0	$Q = 33783\ (\Delta P/T)^{1/2}$	±1.4
10	$Q = 27861\ (\Delta P/T)^{1/2}$	±1.3
15	$Q = 26074\ (\Delta P/T)^{1/2}$	±2.6
20	$Q = 23464\ (\Delta P/T)^{1/2}$	±0.86
30	$Q = 17840\ (\Delta P/T)^{1/2}$	±0.88
Combined Results		
$0^\circ \le P_s \le 30^\circ$	$Q = (33638-522\ P_s)(\Delta P/T)^{1/2}$	±1.4
$P_s > 30^\circ$	$Q = 17978\ (\Delta P/T)^{1/2}$	

NOTE:

Q = [SCFM]
ΔP = [in H_2O]
T = [^oR]
P_s = [Degrees from Open]

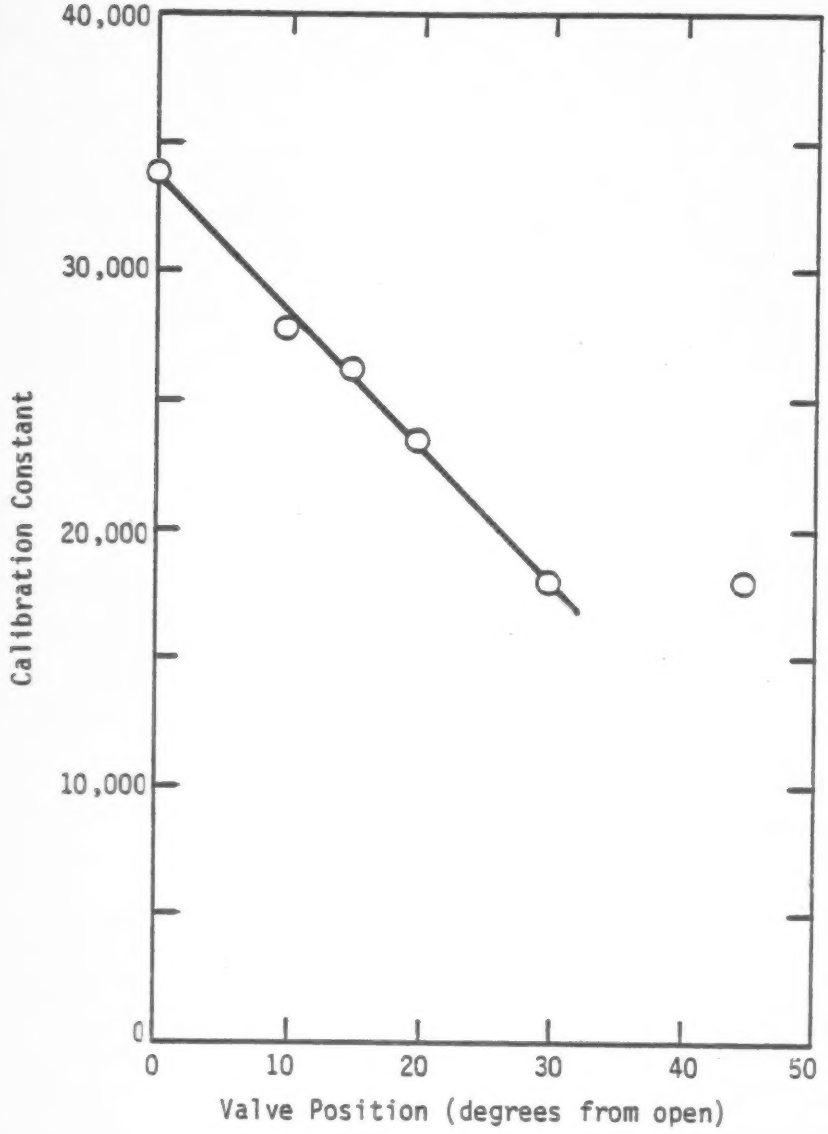


Figure D-15. Calibration constant for outboard tertiary air port control valve.

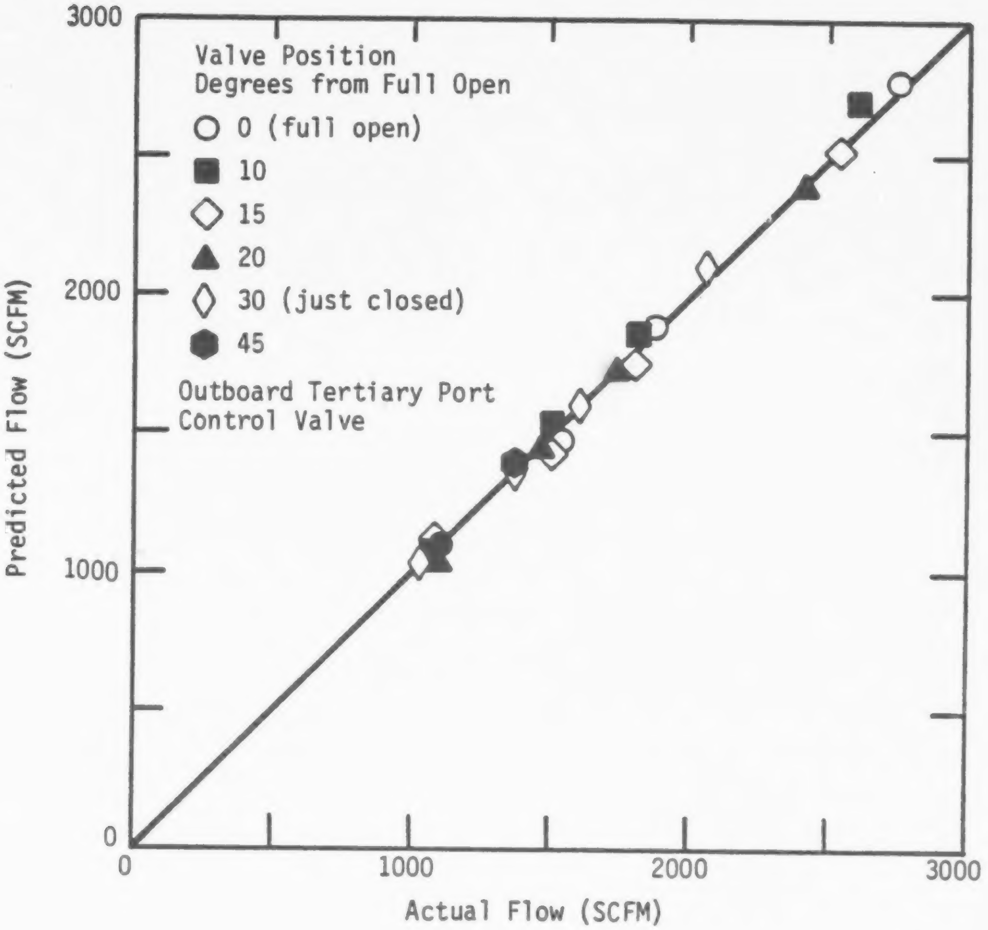


Figure D-16. Comparison of flowrate predicted by correlation and measured flowrate.

Similar calibrations were conducted for the other two cylindrical control valves. The data and correlations are shown in Figures D-17 and E-18 and Tables D-7 and D-8.

The calibration data for the lower tertiary air port control valve is shown in Figure D-19 and the correlations with valve position are shown in Table D-9. For this valve, the relationship between the calibration coefficient and valve position is non-linear. Figure D-20 is a log-log plot of calibration constant versus valve position. The line shown through the data is a regression analysis fit using the relationship $K = A\ P_d^m$ where A and m are constants. Table D-9 lists this overall correlation which fits the data with a standard deviation of 8.8 percent.

The calibration correlation for the tertiary air port control devices as well as the core and register control devices are summarized in Table D-10. There are two correlations for each control device. One relates the air flow rate through the burner passage to the indicated pressure drop and control device setting. This type of correlation was used to calculate the air flow rate through each burner passage during the WIPCO field tests. The other correlation is the relationship between air flow rates and windbox to furnace pressure differential for various burner settings. This correlation was used to calculate the air flow rates and windbox pressure which would be produced by specific burner settings.

D.4 Control System Operation and Recommendations

The results of these calibrations should be interpreted in the context of the DMB design objectives. It was not intended to develop an optimum DMB flow measurement system but rather to adapt Foster Wheeler commercial components to the DMB application. Thus, some compromises were expected.

In Foster Wheeler commercial applications, the sliding sleeves and perforated plate air hoods are used primarily to balance the air flows to the burners supplied from a common windbox. This requires only a 5-10 percent change in air flow rate to each burner. Thus, these components are designed

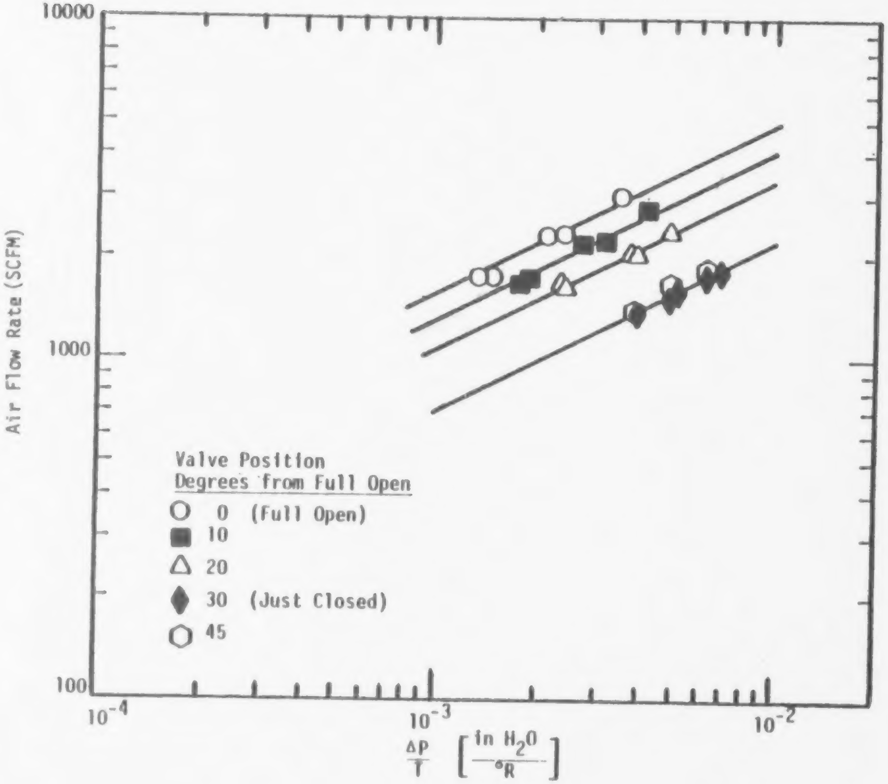


Figure D-17. Upper tertiary air port control valve calibration data.

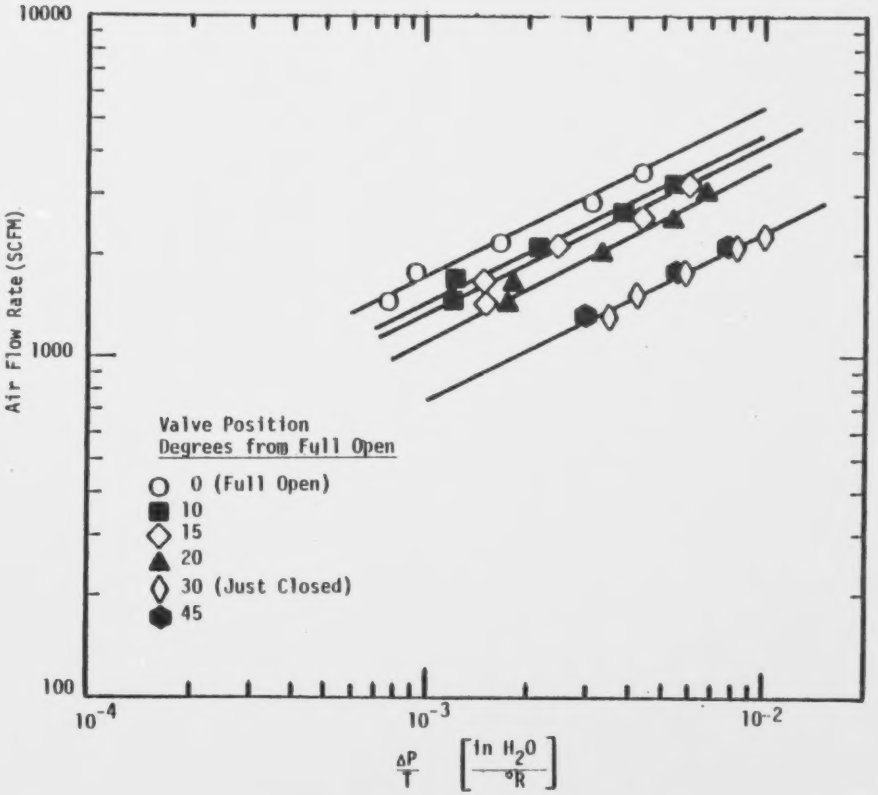


Figure D-18. Center tertiary air port control valve calibration data.

TABLE D-7. AIR FLOW RATE CORRELATION - UPPER TERTIARY AIR PORT CONTROL VALVES

Sleeve Position (Deg. from Open)	Flow Rate Correlation	Standard Deviation (%)
0	$Q = 48775\ (\Delta P/T)^{\frac{1}{2}}$	±4.2
10	$Q = 41343\ (\Delta P/T)^{\frac{1}{2}}$	±3.3
20	$Q = 34222\ (\Delta P/T)^{\frac{1}{2}}$	±2.9
30	$Q = 22243\ (\Delta P/T)^{\frac{1}{2}}$	±1.7
45	$Q = 23378\ (\Delta P/T)^{\frac{1}{2}}$	±3.3
Combined Results		
$0^0 \leq P_s \leq 30^0$	$Q = (49653\text{-}867\ P_s)(\Delta P/T)^{\frac{1}{2}}$	±4.0
$P_s > 30^0$	$Q = 23643\ (\Delta P/T)^{\frac{1}{2}}$	

NOTE:

Q = [SCFM]
ΔP = [in H_2O]
T = [^oR]
P_s = [Degrees from Open]

TABLE D-8. AIR FLOW RATE CORRELATION - CENTER TERTIARY AIR PORT CONTROL VALVE

Sleeve Position (Deg. from Open)	Flow Rate Correlation	Standard Deviation (%)
0	$Q = 53939 (\Delta P/T)^{1/2}$	±3.8
10	$Q = 45478 (\Delta P/T)^{1/2}$	±5.8
15	$Q = 42306 (\Delta P/T)^{1/2}$	±4.5
20	$Q = 36283 (\Delta P/T)^{1/2}$	±5.4
30	$Q = 23185 (\Delta P/T)^{1/2}$	±1.3
45	$Q = 24900 (\Delta P/T)^{1/2}$	±1.1
Combined Results		
$0^0 \leq P_s \leq 30^0$	$Q = (55457-1015\ P_s)(\Delta P/T)^{1/2}$	±4.2
$P_s > 30^0$	$Q = 25007 (\Delta P/T)^{1/2}$	

NOTE:

Q = [SCFM]
ΔP = [in H_2O]
T = [^oR]
P_s = [Degrees from Open]

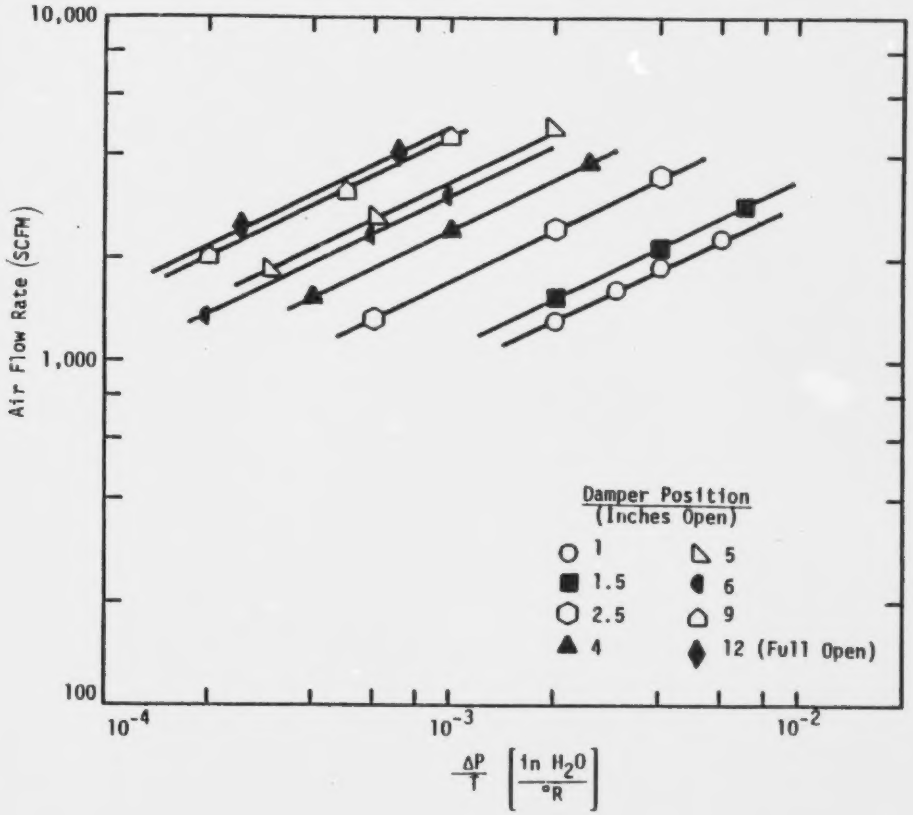


Figure D-19. Lower tertiary air port control valve calibration data.

TABLE D-9. AIR FLOW RATE CORRELATION - LOWER TERTIARY AIR PORT CONTROL VALVE

Damper Position (Inches Open)	Flow Rate Correlation	Standard Deviation (%)
1	$Q = 29635 (\Delta P/T)^{1/2}$	±11.6
1.5	$Q = 34285 (\Delta P/T)^{1/2}$	±12.4
2.5	$Q = 54793 (\Delta P/T)^{1/2}$	± 1.9
4	$Q = 76630 (\Delta P/T)^{1/2}$	± 4.4
5	$Q = 105051 (\Delta P/T)^{1/2}$	±12.5
6	$Q = 97814 (\Delta P/T)^{1/2}$	± 7.8
9	$Q = 142824 (\Delta P/T)^{1/2}$	± 5.1
12	$Q = 152862 (\Delta P/T)^{1/2}$	± 6.5
Combined Results		
$0 \le P_d \le 12"$	$Q = 28501 P_d^{0.7131} (\Delta P/T)^{1/2}$	± 8.8

NOTE:

Q = [SCFM]

ΔP = [in H_2O]

T = [^oR]

P_d = [Inches Open]

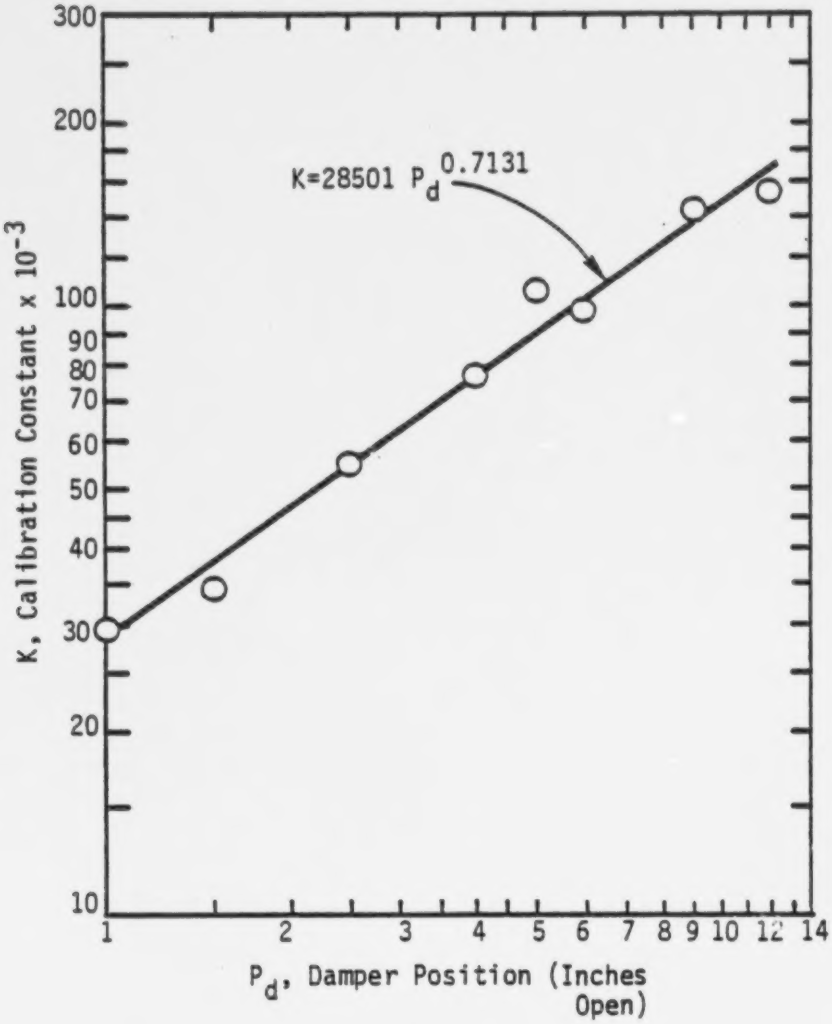


Figure D-20. Calibration constant for lower tertiary port control valve.

TABLE D-10. CALIBRATION SUMMARY

Burner Passage	Flowrate Correlation $Q = (K)(\Delta P_i/T)^{\frac{1}{2}}$**	Windbox to Furnace Pressure Drop $Q = (K)(\Delta P_{wb}/T)^{\frac{1}{2}}$**	Control System Variables
Core	$18500 - 182\ P_v$	$18500 - 182\ P_v$	P_v = Degrees from Full Open
Outer Secondary*	$96000 + 1430\ P_s$	$202000 - 1970\ P_r$	P_r = Degrees from Full Open
Inner Secondary*	$509 + 751\ P_s$	$(0.64+0.0036\ P_s)x(93200-515\ P_r)$	P_r = Degrees from Full Open P_s = Percent Open
Upper Tertiary	$49653 - 867\ P_s$	$49653 - 867\ P_s$	P_s = Degrees from Full Open (0-30)
Outboard Tertiary	$33638 - 522\ P_s$	$33638 - 522\ P_s$	P_s = Degrees from Full Open (0-30)
Center Tertiary	$55457 - 1015\ P_s$	$55457 - 1015\ P_s$	P_s = Degrees from Full Open (0-30)
Lower Tertiary	$28501\ P_d^{0.7131}$	$\left\{\frac{(28501\ P_d^{0.7131})^2}{1+\left(\frac{7.99525x10^{-7}}{T}\right)(28501\ P_d^{0.7131})^2}\right\}^{\frac{1}{2}}$	P_d = Inches from Closed (0-12)

NOTE:

Q = SCFM
ΔP_{wb} = in H_2O
ΔP_i = in H_2O
T = ^oR

* Windbox pressure data are based on Prototype 1 calibrations. The changes in exit geometry in Prototype 2 may affect these results.

** K = Relationships for coefficient.

to provide minimal restriction and typically operate at greater than 50 percent open. In this operating range, the clearance between the sleeve and perforated plate is not critical. The sleeves are adjusted during optimization tests to balance the burners and are then tack welded into position.

A key design aspect is to achieve balance with minimum flow restriction and low windbox to furnace pressure differential. However, in the DMB application, the sleeves were intended to provide an additional function of restricting the secondary air flow rates so as to increase the windbox-to-furnace differential and reduce burner zone stoichiometry. This required operating with the sleeves almost or fully closed. Even under these conditions, the sleeve flow restriction was low and it was necessary to use the registers to provide additional restriction. Also, in the nearly or fully closed positions, the major flow restrictions in the sleeve/perforated plate combinations are the clearances between the sleeves and perforated plates rather than the effective open areas of the perforated plates. Thus, variations in clearance due to manufacturing tolerances may have impacted the calibrations.

The pressure drop across the sleeves and air hoods was measured between pressure taps in the windbox and between the perforated plates and registers. Under normal operating conditions with the sleeves over 50 percent open, the precise locations of these pressure taps are unimportant. However in the DMB application where the sleeves and registers were nearly fully closed, the positions of the inner pressure taps were probably critical. Any misalignment between a sleeve and associated perforated plate causes a circumferential variation in air flow rate and pressure. Also, the jetting action of the flow through the nearly closed register changes the pressure distribution in the vicinity of the inner pressure tap. This accounts for the sensitivity of the sleeve calibration to register position outside the normal commercial operating range of 30-60° open.

Commercial registers normally serve two functions: control of secondary air swirl and air flow shut off when burners are removed from service. To avoid burner overheating when burners are out of service, the registers are designed with liberal clearances to provide leakage air flow. Under normal operation, the registers are set about half open and are adjusted to provide swirl commensurate with the desired flame shape. The majority of the air flowing through the register passes along the register vane contours. As the register is adjusted towards the closed position, the pressure drop across the register increases and a portion of the flow bypasses the vanes through the clearances. Thus, the swirl produced by the register is less than would be expected if all the flow passed along the vane contours. In the nearly or fully closed position, a substantial fraction of the air flow bypasses the vanes and the total swirl may actually decrease. The register calibration indicates that the swirl angles for the DMB registers are essentially constant from 30-75° from fully open. It should be noted that swirl angle measurements in the burner throat are difficult. The swirl angle varies with radial and circumferential position. Also, the swirl depends not only on the register position but also on the burner exit design. Thus, the swirl measurements which were conducted using the initial prototype DMB are not necessarily representative of the swirl produced by the DMB with Foster Wheeler exit geometry (which was installed at WIPCO) and the final DMB design.

To achieve low burner zone stoichiometries during the staged tests at WIPCO, it was necessary to operate with the registers nearly or fully closed to divert air to the tertiary air ports. This is outside the normal range of register operation. Thus, while in most commercial installations changes in register positions affect primarily swirl, in the DMB installation at WIPCO changes in register settings primarily impacted flow restriction which changed burner balance and burner zone stoichiometry.

The tertiary air port control and flow metering components were not adaptations of commercial burner components but were new designs specifically for the DMB application. The design used for the prototype burner test has the advantage of a fixed opened area for the measurement of pressure drop and a separate flow control damper (poppet valve). This provided excellent accuracy of flow measurement and a single calibration independent of control position. The poppet valve was effective in controlling the air flow rate and could be adjusted to provide near zero air leakage. This allowed operation of the prototype DMB under staged as well as unstaged conditions. However, due to the limited space available in the windbox and concern over possible overheating of the poppet valve assembly, an alternate design was used for the WIPCO installation.

The design used for the WIPCO installation also provided excellent flow rate metering accuracy but required accurate specification of control valve geometry and position. The circular control valve did not provide for a wide flow rate adjustment range due to the liberal clearances used and high leakage air flow rates with the valves closed. Varying the valve positions from full closed to full open changed the flow rate by about a factor of two at fixed windbox-to-furnace differential pressure. The lower tertiary air port control system (sliding plate assembly) provided better control and could be set to very small leakage air flow.

Based on these considerations, it is recommended that future DMB installations use alternate air flow control systems. The key considerations are as follows:

- more effective control of burner zone stoichiometry
- air flow rate measurements independent of control position

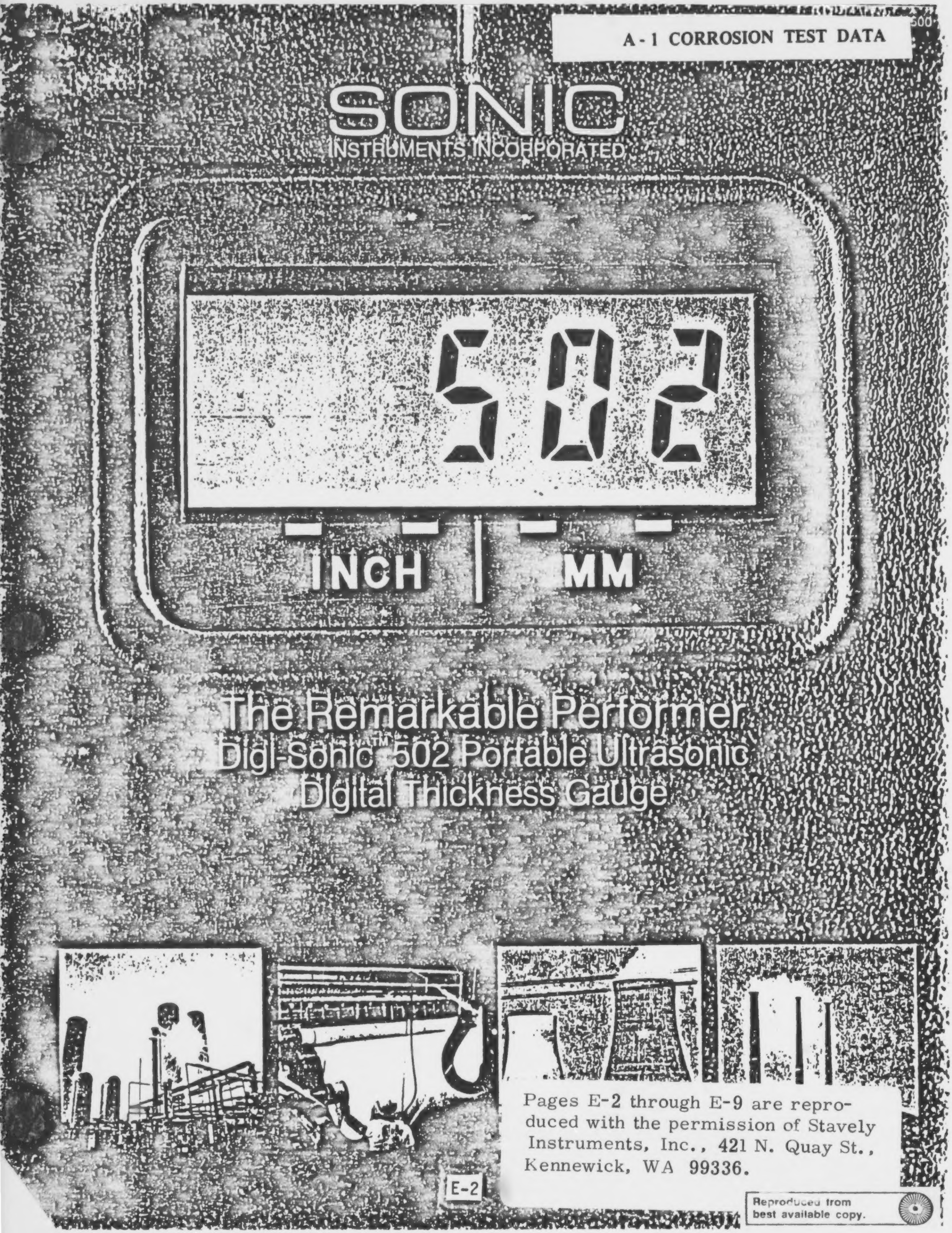
Since burner zone stoichiometry is the key parameter influencing burner performance, it would be most desirable to control burner zone stoichiometry independent of the parameters which affect burner balance and flame stability such as the secondary air swirl. Such control could be achieved by utilizing a divided windbox where the burner throats and tertiary air ports are supplied with air from separate plenums with separate air flow controls. Additional controls would be needed on each burner passage for flow balancing. These would be adjusted during start up and optimization only and no power drives would be required. The controls would require only moderate restriction well within the range of the type of equipment used in this program. Such a divided windbox would complicate windbox design and was ruled out at WIPCO for this reason. However, on a new installation, it would be very attractive. Alternately, a common windbox system could be used. This would require burner flow rate controls which provide a wide range of flow control particularly if staged and unstaged operation was required. Specifically, variable restrictions would need to be provided on both the tertiary air ports and burner throat passages to maintain windbox-to-furnace pressure differential in the desired range for both staged and unstaged conditions. For an overall stoichiometry of 120 percent TA and a burner zone stoichiometry range of 50 - 115 percent TA, the effective opened area of the tertiary air ports would need to be varied by a factor of 14. This is substantially greater than the factor of two range achievable with the circular tertiary air ports used for all but the lower four ports at WIPCO. Similarly, the air flow restrictions for burner passages supplying the throat (including the core and inner and outer registers) would need to be variable over a range of three to one.

Most of the air flow rate measurements systems in this program involved measurement of the differential pressure across a variable restriction. The calibration varied with controlled position and thus, it was necessary to specify the control positions accurately. This was difficult due to a number of factors such as loss motion in the linkages, manufacturing tolerances, thermal expansion, accuracy of the indicators and cocking of some components. This would be a particular problem for control devices where restriction varied by large factors as discussed in the previous paragraph. In this case, the control device positions would need to be known very accurately, particularly under conditions where they are nearly fully closed. If the air flow rate control and measurement functions are separated, the need to accurately specify control positions is eliminated. Flow balance and flow rate changes could be determined directly. Thus, for future designs it is recommended that the flow rate control and measurement functions be achieved separately for each flow passage.

APPENDIX E

CORROSION DATA

The field evaluation included a multi-year assessment of tube wastage in the furnace. Data were obtained over time periods where the original equipment and DMBs were operating over a range of conditions. This appendix presents the tube thickness data obtained throughout the program. An analysis of these data comparing tube wastage rates for the two burner designs is presented in Section 4 of Volume I of the final report.



The Remarkable Performer

Digi-Sonic™ 502 Portable Ultrasonic Digital Thickness Gauge

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Digi-Sonic 502 Unmatched capabilities.

Quick, easy operation.

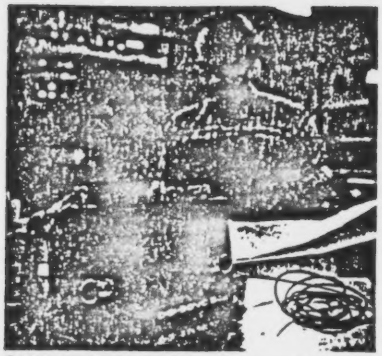
Sonic's new Digi-Sonic 502 is the most advanced ultrasonic testing device of its kind available anywhere. A highly versatile, digital thickness gauge, the 502 easily out performs all other available units both in the types of tests it can handle and the range of industries in which it can be used. This is due to the 502's remarkable flexibility and ease of operation. It does the job of several thickness gauges, zeroing in with exact readings, regardless of the thickness, condition or temperature of the test material.

A practical answer.

Sonic's remarkable new unit delivers state-of-the-art ultrasonic testing technology in a sophisticated, compact package. The Digi-Sonic 502 can provide any industry with a practical and economical solution to its non-destructive testing problems—from preventive maintenance to corrosion testing to material evaluation and quality control.

Quick calibration, easy operation.

This lightweight, portable, battery-operated unit is simple and easy to operate. The 502 is just as effective in the hands of an operator with no previous training in ultrasonic technology and application as it is in the hands of a skilled professional. Once the 502 is calibrated, the rest of the operation is a snap. The mode switch is adjusted to match the transducer and the calibration and velocity controls are set to accommodate the transducer wearplate and material types. No other settings are necessary.

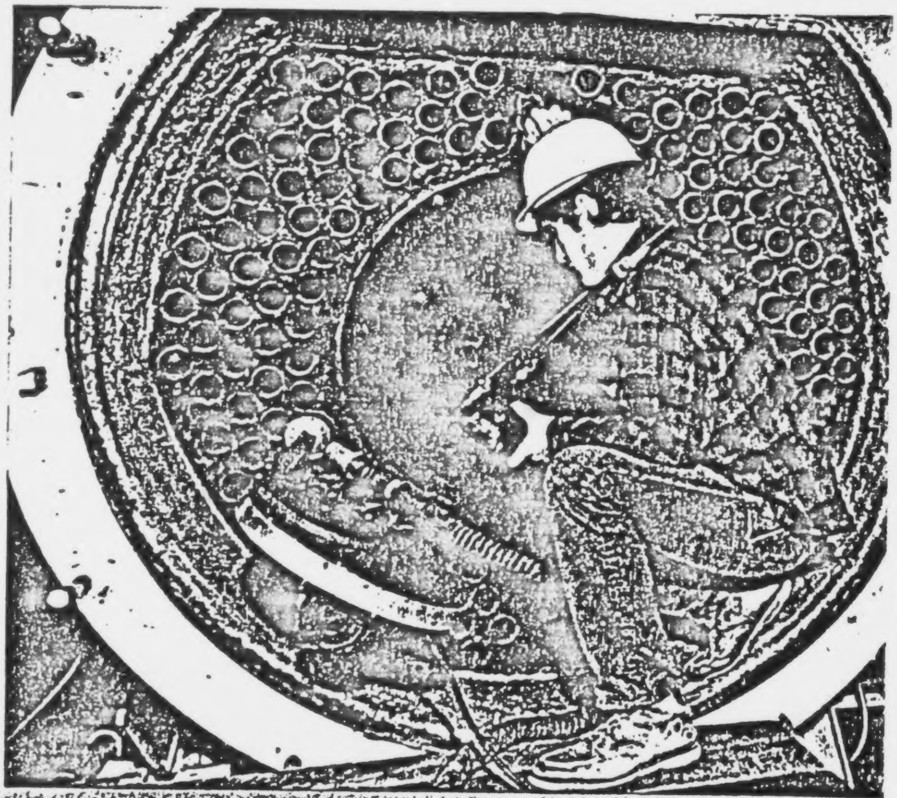


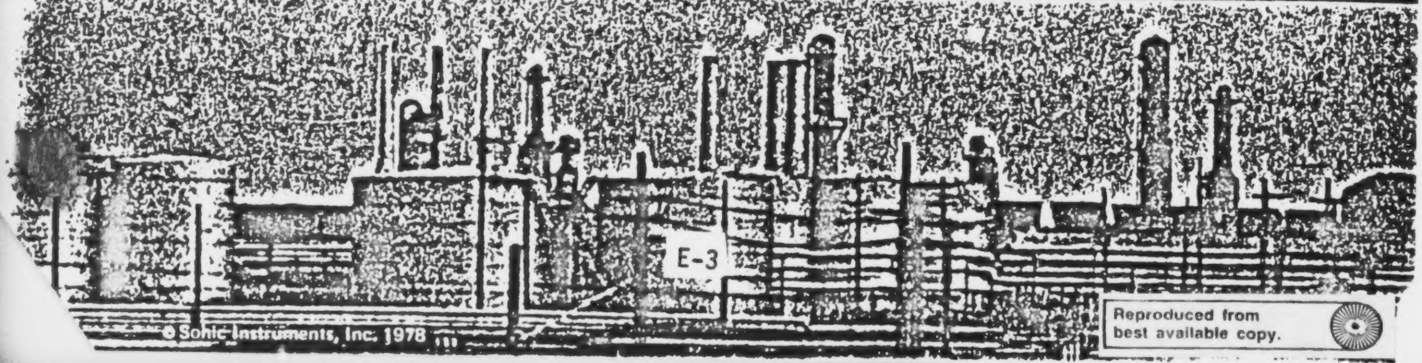
QUALITY CONTROL: High precision thickness gauging of critical sheet metal.

Tough, compact design.

Rugged unit construction, exceptional stability, a crystal time base and quick, error-free readout are some of the Digi-Sonic 502's significant design features. An operating temperature range of -4°F to 131°F (-20°C to 55°C) assures reliable performance under the toughest of environmental conditions. The 502 is self-contained in a sturdy, drip-and dust-proof enclosure for easy, reliable on-site use. It weighs in at just 3 lbs. 4 oz. (1.47 kg) and measures a super compact 7.2" x 4.4" x 2.6" (18.3 x 11.2 x 6.6cm).

PREVENTIVE MAINTENANCE: In-service boiler inspection for pitting and corrosion.





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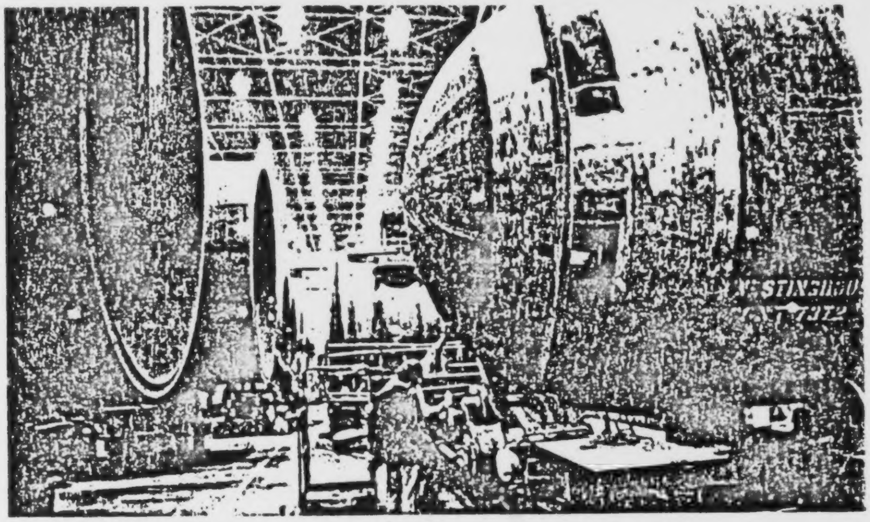
Reliable battery operation.

An internal, 5.6V nickel cadmium battery pack provides sufficient power for 8 hrs. of continuous use. The external charger supplied with each unit restores the battery pack to peak charge in 10 to 12 hrs. Battery charge condition can be monitored on digital readout.



PRODUCTION CONTROL: Thickness gauging of heavy-walled nuclear container.

Easy reading LCD.

The 502's large four and a half-digit liquid crystal display (LCD) provides easy readability in bright sunlight or subdued lighting. The display actually becomes easier to read in direct light.

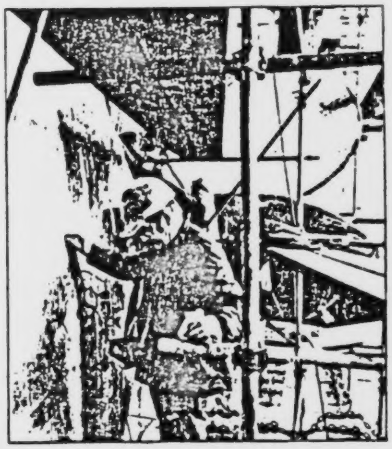
Precision and wide range.

The Digi-Sonic 502 has a thickness measurement range of .015" to 19.999" (.38mm to 1000mm) in steel with low range readout resolution of ± .0001" (± .0025mm) or high range readout resolution of ± .001" (± .025mm) or 0.02% of actual reading.

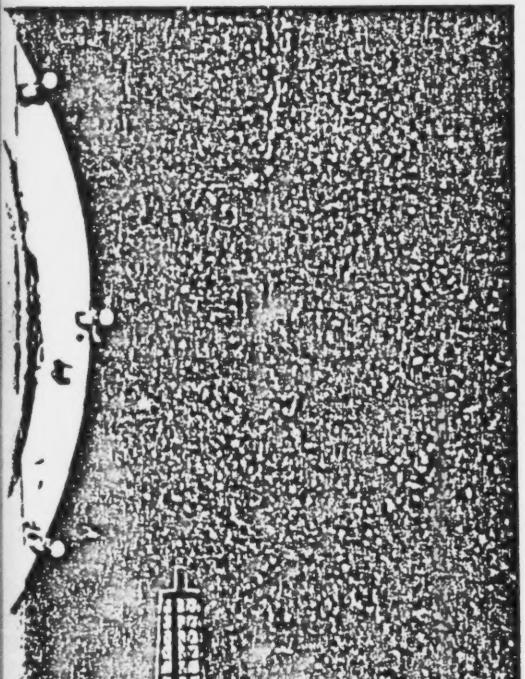
*Measurement ranges .010" (or .25mm) available on request.

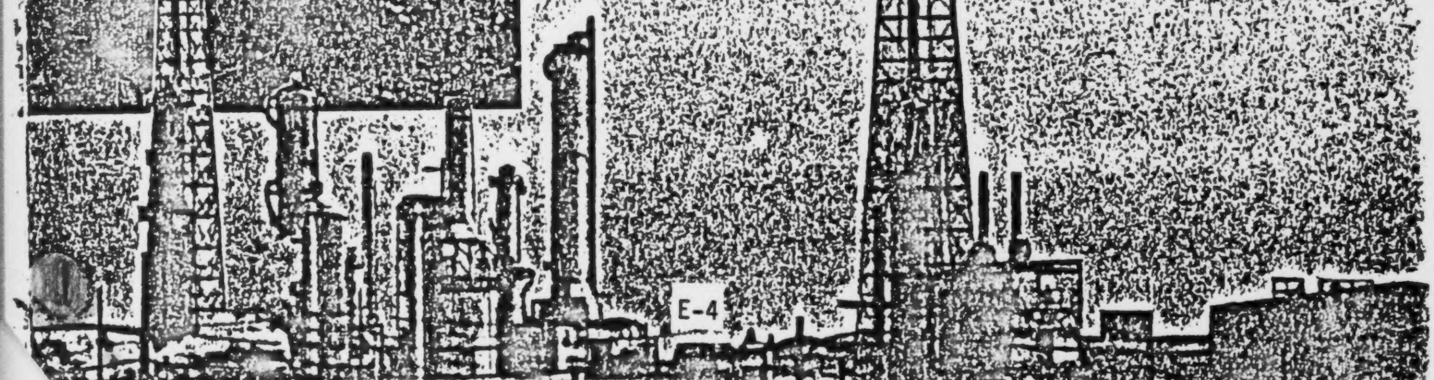
Quick Inch or Metric readings.

The 502's circuitry is designed to provide readings in both inch and metric measure, without the need to reset or recalibrate. This eliminates guesswork and extra calibration steps and reduces overall testing time.



QUALITY ASSURANCE: Thickness gauging of ship hull plate in critical propeller shaft location.





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A gauge for all reasons.

The 502's unique circuit design makes it compatible with contact, delay and dual transducers, and accounts for its exceptional versatility. It can go from thick to thin . . . hot to cold without losing accuracy or repeatability.

Difficult measurement applications.

The 502's sensitivity and stability make it a useful tool in gauging applications where contour, shape, finish or accessibility make testing difficult. Key applications include testing of U-bend areas on steam generator tubing, curved aircraft turbine blades, tapered and curved "D" spar helicopter blades and corroded structural members on bridges and oil tankers.

Corrosive environments.

Compatibility with dual element transducers makes this thickness gauge well-suited for determining remaining wall thickness of pipes and vessels. The gauges ability to precisely measure corroded and pitted materials makes it extremely valuable to the maintenance function in the gas, petroleum, chemical and fluid transmission and storage industries.

Precise thin material measurement.

A highly damped delay line transducer makes the versatile 502 capable of a high degree of precision in measurement of thin materials such as: machined parts, aerospace skins and hydraulic lines, precision castings, thin sheet extrusions and plate stock.

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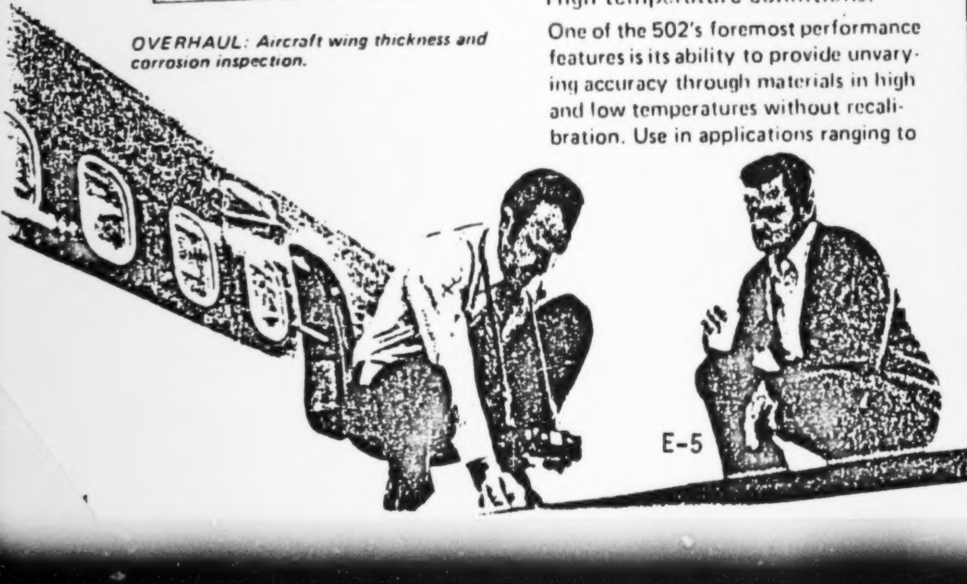
***OVERHAUL:** Aircraft wing thickness and corrosion inspection.*



Hard-to-reach areas.

Hard to-reach or confined test locations offer no challenge to the Digi-Sonic 502 because of two significant features: compatibility with a wide variety of miniature transducers and a unique display "Hold" feature. The measurement displayed on initial contact is held until contact is made again—a "human engineering" design feature that will come in handy for oil and gas pipeline, power transmission and other industrial maintenance personnel.

Massive metallic components.

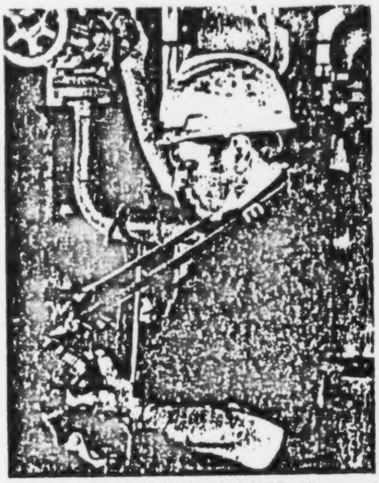
In nuclear, marine and foundry-type industries where large metal parts such as billets, bar stock and forgings are handled daily, the 502 is a real "problem solver." Twenty inches in steel is the unit's top end in hi-penetration tests. Special Sonic product engineering allows the 502 to be used with a wide variety of low frequency, large transducers.

Quick velocity changes.

A special velocity display mode has been built in to eliminate lengthy recalibration. In other units, calibration without a velocity display requires two known thickness standards of the material to be tested. The operator must adjust velocity and wearplate offset each time he changes materials. The Digi-Sonic 502 can easily make the change from structural automotive plastic to stainless steel sheet metal without time consuming recalibration. A simple resetting of the velocity controls can take you from wood to lead to plastic or even beryllium.

High temperature conditions.

One of the 502's foremost performance features is its ability to provide unvarying accuracy through materials in high and low temperatures without recalibration. Use in applications ranging to 1000°F (537.7°C) is possible with Sonic's specially designed high temperature, delay line transducers.



***PREVENTIVE MAINTENANCE:** Chemical plant corrosion and thickness maintenance survey.*

Flexibility, ease of operation, portability, precision, wide measurement range—an unmatched combination of design and performance features which makes the new 502 the most advanced instrument of its kind.

***IN-PROCESS TESTING:** Thickness gauging during m*

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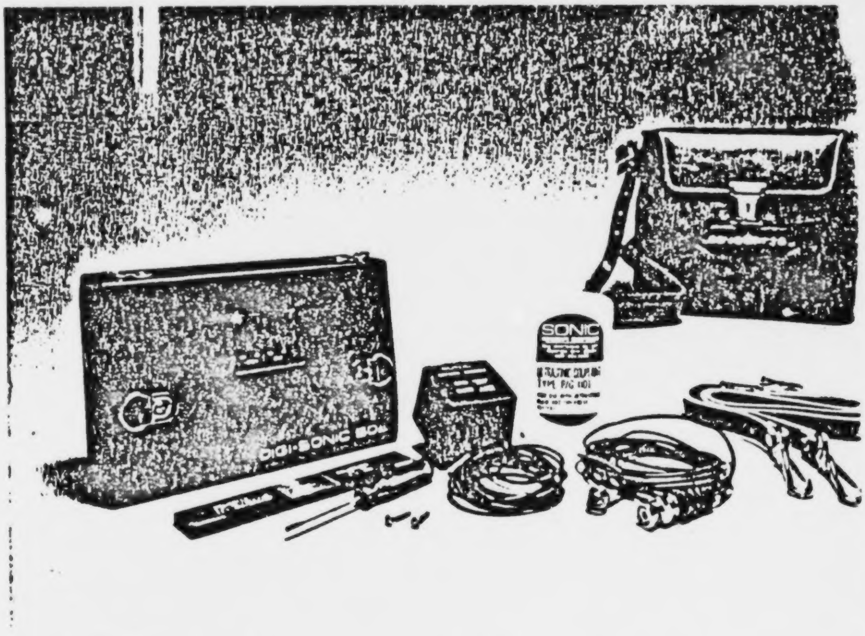
Digi-Sonic 502 Standard Equipment

The following equipment is included in the basic Digi-Sonic 502 Equipment Set, Cat. No. DG502A.

1. **Digi-Sonic 502 Thickness Gauge**
2. **Protective leather cover and carry strap**
3. **Rechargeable battery pack**
4. **Battery charger:** 10–12 hrs., 120/230 V
5. **Transducer:** Type CBA, 5 MHz, .25" (6.35mm) element diameter, microdot connector
6. **Coaxial cable:** BNC to microdot, 6 ft. (1.83m) length
7. **Reference block:** Thickness and velocity calibration
8. **Bottle of couplant**
9. **Rugged carrying case**
10. **Operating manual**
11. **Calibration certificate**



The Digi-Sonic 502 is provided in a complete set which includes carrying case and all necessary accessories.

shop set-up.

Digi-Sonic 502 Specifications

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Display: 4½ digit liquid crystal.

Test Modes:

1. **Contact Transducers (steel)**
   Resolution—Normal usage: .0500 to 19.999" (1.270 to 1000mm)
   Power—Difficult surfaces and penetration: .300 to 19.999" (7.62 to 1000mm)

2. **Delay Tip Transducers (steel)**
   Delay 1—Interface to first echo: .1000 to .5000" (2.540 to 12.700mm)

   Delay 2—Multi-echo for thin materials: .0151* to .2500 (.36* to 6.35mm)

3. **Dual Transducers (steel)**
   Dual—Rough back surfaces: .0500 to 19.999" (1.270 to 1000mm)

Thickness Ranges and Accuracy:

2 in.: .0150* to 1.9999"
(± .0001" or ± .02% of reading)

20 in.: .015* to 19.999"
(± .001" or ± .02% of reading)

200mm: .38* to 200.00mm
(± .01mm or ± .02% of reading)

1000mm: .38* to 1000.0mm
(± .1mm or ± .02% of reading)

Velocity Range—0.0000 to 5.500 × 10^5 in./sec. (14.000 × 10^5 mm/sec.)

Calibrate (Delay) Range—0 to .5" (12.7mm) steel.

Receiver Bandwidth—15 MHz.

Receiver Gain—AGC: 100 dB max.

Pulse Repetition Rate—976.6 Hz crystal controlled.

Damping—Automatic.

Interchangeable Battery Pack—Ni-cad batteries.

Operation—8 hrs. min. continuous

Full charge—10–12 hrs.

Operating Temperature Range—
-4°F to 131°F (-20°C to 55°C)

Overall Dimensions—
7.2" W x 4.4" H x 2.6" D
(18.3 x 11.2 x 6.6cm)

Weight—3 lbs. 4 oz. (1.47 kg)

Ordering Information: Contact:
Sales Department, Sonic Instruments, Inc., 1018 Whitehead Rd. Ext.,
Trenton, NJ 08638 (609) 883 5030
Telex: 843391.

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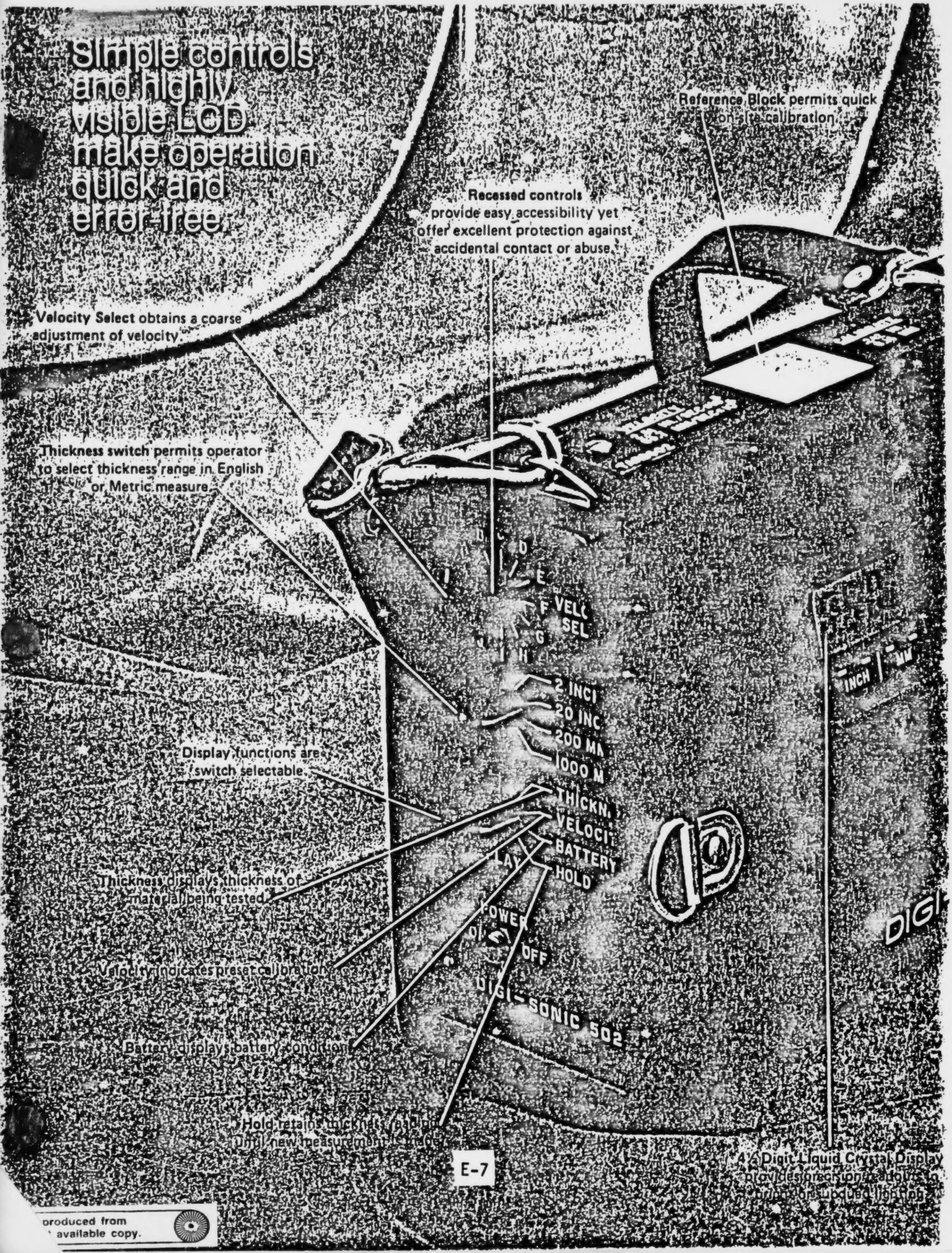
*Resolution of .0100" (.25mm) optional

Simple controls and highly visible LCD make operation quick and error-free.



Reference Block permits quick on-site calibration.

Recessed controls provide easy accessibility yet offer excellent protection against accidental contact or abuse.

Velocity Select obtains a coarse adjustment of velocity.

Thickness switch permits operator to select thickness range in English or Metric measure.

Display functions are switch selectable.

Thickness displays thickness of material being tested.

Velocity indicates preset calibration.

Battery displays battery condition.

Hold retains thickness reading until new measurement is made.

4½ Digit Liquid Crystal Display provides precision readouts in bright or subdued lighting.

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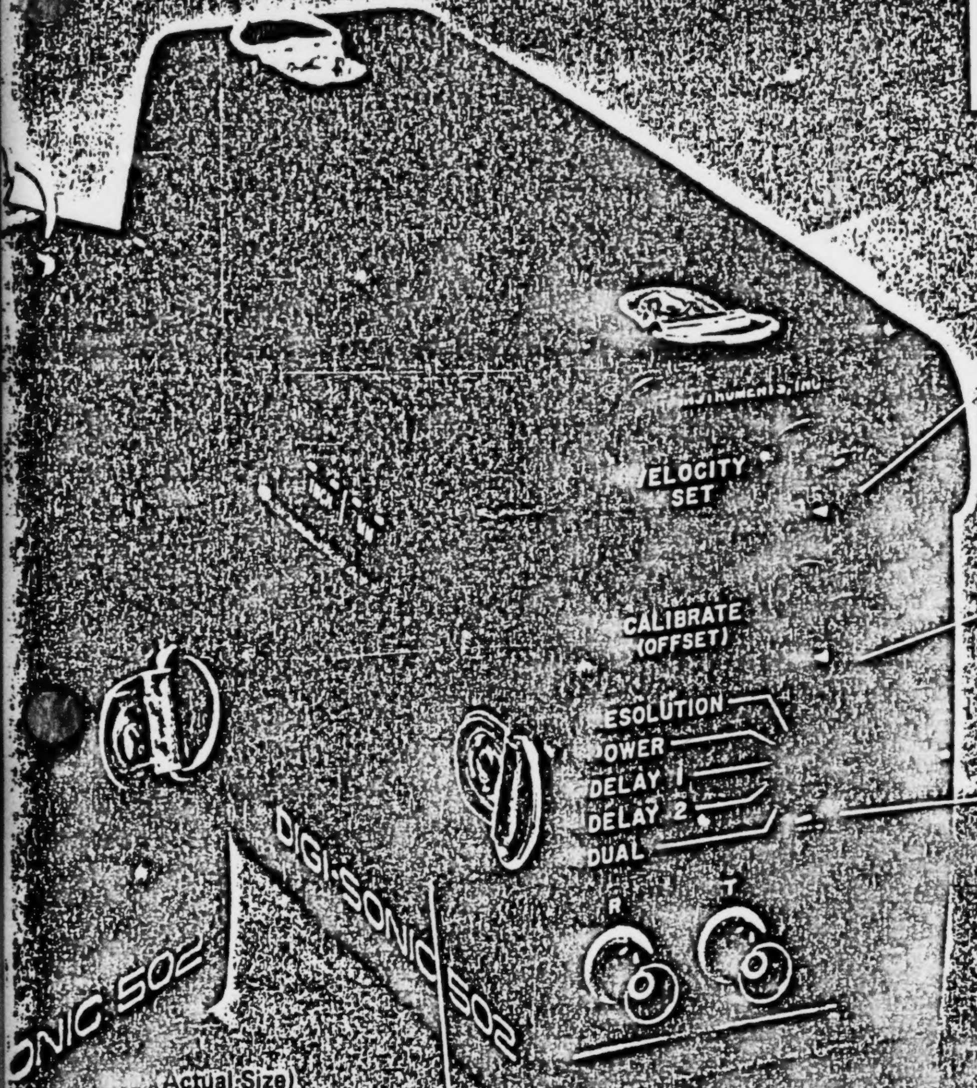
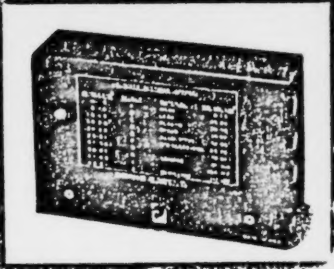


Actual Size)



Velocity Settings chart indicates settings for coarse velocity adjustments.

Velocity set switch uses ten-turn potentiometer for fine adjustment of velocity calibration.

Calibrate (offset) control compensates for transducer tip and wearplate variations from 0 to .5" (12.7mm) in steel.

Mode is selected by quick set five position switch which matches instrument to transducer and intended test.

Leather case withstands rugged on-site use.

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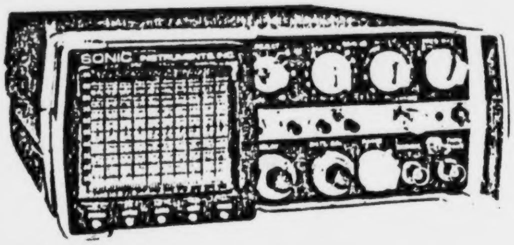
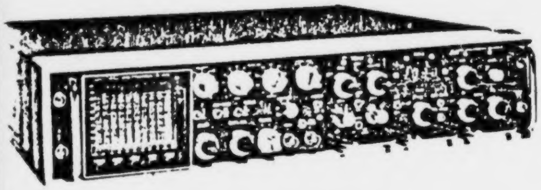
Sonic has the sound solution for ultrasonic test systems.

The complete Sonic line of testers includes instruments and systems designed for a broad variety of applications and environments.

Sonic engineers will help you in determining which instrument or system will best suit your applications, or in solutions to specific material test problems.



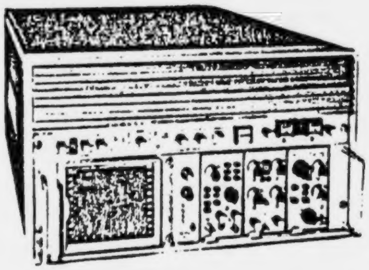


Mark I and Mark I/220 Ultrasonic Testers bring laboratory standards of accuracy to in-field testing and measurement. They're the portable minis that are big on performance and value.

Overall dimensions: 9.5" x 3.75" x 13" deep.
(24.13cm x 9.53cm x 33.02cm)

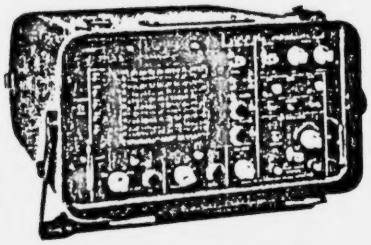
Mark II Ultrasonic Testing Systems offer the advantages of true modular design, resulting in custom systems that avoid problems of inflexibility and obsolescence. Multiplex systems and NEMA enclosures further extend their capabilities.

Overall dimensions: 19.5" x 4.5" x 20.75" deep.
(49.53cm x 11.43cm x 52.7cm)



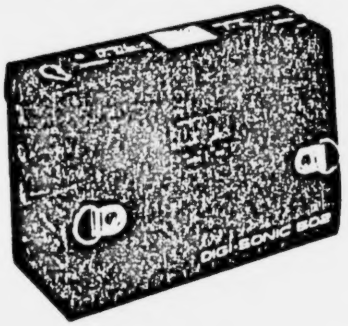
Mark III Modular Ultrasonic Flaw/Thickness/Velocity Testers surpass other instruments in precision, resolution and versatility. Nineteen separate plug-ins permit a "building block" approach to perform the widest range of functions. Up to six additional functions can be built into the Mark III Adapter section which interfaces with your system and contains DEC, recorder drive and alarm logic.

Overall dimensions: 19.75" x 11" x 35" deep.
(50.7cm x 27.94cm x 63.5cm)



Mark IV Ultrasonic Flaw Detectors are manufactured for performance and reliability under tough field conditions. Originally designed to rigid military specifications, these big screen, battery operated portables feature modular internal construction with all subassemblies interconnected via plugs. "Throw away" PC boards and screwdriver disassembly make the unit completely field serviceable.

Overall dimensions: 14.5" x 7.875" x 20" deep
(36.2cm x 20cm x 50.8cm)



Digi-Sonic 502 Ultrasonic Digital Thickness Gauges are designed for industry-wide use under tough on-site conditions. Unmatched flexibility and simple operation are the units' key features. Clear, easy-to-read 4½ digit LCD's and compatibility with a variety of transducers extend their capabilities beyond simple thickness gauging.

Overall dimensions: 7.2" x 4.4" x 2.6" deep.
(18.3cm x 11.2cm x 6.6cm)

Ultrasonic Transducers. Sonic offers hundreds of different transducers for ultrasonic flaw detection and thickness measurement. Contact, immersion and angle beam models as well as fixtures, cables and other accessories are described in a free Applications Guide, available from Sonic Instruments.

SONIC IS SOUND

SONIC

INSTRUMENTS INCORPORATED

1018 Whitehead Road, Ext., Trenton, NJ 08638
Telephone: (609) 883-5030 Telex: 843391

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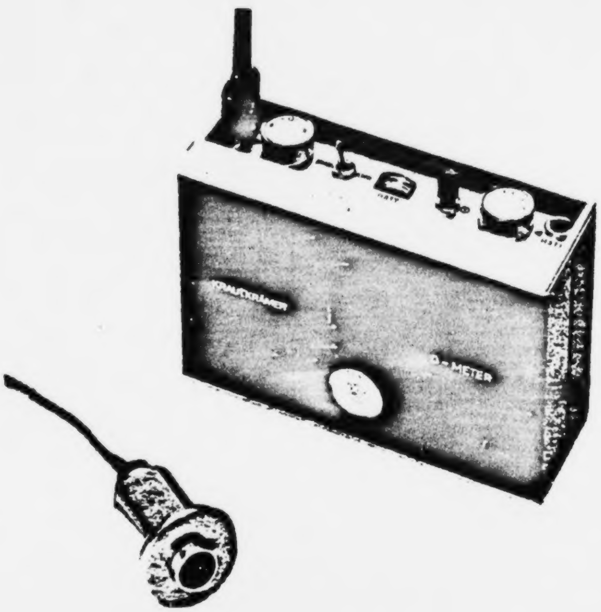
OPERATING INSTRUCTIONS

Second Edition

TYPE DM-1B

Portable Digital Ultrasonic Wall Thickness Gauge



KRAUTKRAMER-BRANSON, INCORPORATED
subsidiary of SmithKline Corporation
STRATFORD, CONNECTICUT

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April 1979

SECTION I

INTRODUCTION

1-1. INTRODUCTION.

1-2. The Krautkramer-Branson, Incorporated type DM-1B is a portable ultrasonic thickness measuring instrument. It is designed for simplicity in use and can be operated by persons with no special skills or training after just a few moments of instructions. It can provide fast and accurate measurement of thickness on most metals and plastics and requires only access to one side of the material to accomplish these measurements. The DM-1B, or "D-Meter", is especially intended for measurement of remaining wall thickness on pipe, vessels, etc.

1-3. SPECIFICATIONS.

1-4. The technical data and specifications for the DM-1B are listed below:

MEASURING RANGE	0.05 in. to 12 in. (The maximum varies with the sound attenuation of the material being measured.)

PROBE TYPE	TEMPERATURE RANGE °F.	THICKNESS RANGE IN.	NOTES
KMH-4	15 - 940	0.12 - 2.4	High temp. use.
KMR-4	15 - 450	0.05 - 2.4	General use below 2.4 in.
KMR-4V	15 - 750	0.05 - 2.4	General "hot" use.
KMR-4/8	15 - 450	0.05 - 2.4	Smaller contact dia.
KMR-4-958	15 - 212	0.05 - 2.4	Fingertip mounting.
KMS-2	15 - 450	0.6 - 12	For high attenuation material.
KMS-4	15 - 450	0.3 - 12	General use above 2.4 in.
KMS-4V	15 - 750	0.3 - 12	"Hot" use above 2.4 in.
KMS-4/8	15 - 450	0.3 - 12	Small contact dia.
KMS-4-959	15 - 212	0.3 - 12	Fingertip mounting.

NOTE: On curved surfaces the maximum curvature is 0.4 in. radius and minimum wall thickness is 0.08 in. for material below 212°F; above 212°F, the maximum curvature is 1.6 in. radius and the minimum wall thickness 0.2 in.

ACCURACY	± 0.005 in.
TEMPERATURE RANGE OF MATERIAL	Varies with probe used; see above.
READOUT	Four digit LED indicator; the last digit reads only "0" or "5".
MATERIAL WHICH MAY BE MEASURED	Any material with sound velocity between 0.188 - 0.250 in./usec. (2400 - 6364 M/sec.). Calibration is established by internal quartz crystals. The DM-1B is normally supplied with crystals for the range 0.230 - 0.250 in./usec.
MEASUREMENT TECHNIQUE	Ultrasonic pulse-echo with digital time measurement.
CALIBRATION STANDARD	Built-in for steel or aluminum.
POWER REQUIRED	0.6 A at 7.5 V max. Supplied by 5 nicad or dry cells.
BATTERY CHECK	Built-in meter.
DISCHARGE PROTECTION	Automatic shut-off after a maximum of three minutes discontinued use.
HOUSING	Vinyl coated die-cast aluminum.
SIZE	5.7 x 3.9 x 2.0 in.
WEIGHT	2.2 lbs.

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

5/81

Inches From Top	TUBE NUMBER 1	2	3	4	5
Panel No. 1					
2	180	180	175	175	175
24	170	180	175	170	170
46	175	170	175	165	175
Panel No. 2					
2	195	195	190	190	190
24	185	185	195	175	190
46	185	185	190	185	185
Panel No. 3					
2	170	175	180	180	175
24	175	170	180	180	175
46	175	165	180	175	180
Panel No. 4					
2	170	160	170	165	165
24	175	165	170	170	170
46	170	165	160	165	170

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 1
4/82

Inches From Top	TUBE NUMBER 1	2	3	4	5
0	185	180	180	180	175
6	180	175	185	175	180
12	180	180	180	180	175
18	175	180	180	175	175
24	180	175	180	175	175
30	175	175	180	165	180
36	170	175	175	170	175
42	175	175	180	160	180
48	170	170	175	165	180

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 2
4/82

	TUBE NUMBER				
Inches From Top	**1**	**2**	**3**	**4**	**5**
0	175	175	175	170	180
6	185	170	175	175	180
12	175	165	175	170	175
18	180	165	175	175	175
24	175	160	180	170	175
30	175	160	175	175	170
36	180	165	170	170	170
42	170	165	175	170	165
48	175	170	170	170	170

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 3
4/82

	TUBE NUMBER				
Inches From Top	**1**	**2**	**3**	**4**	**5**
0	170	170	175	180	170
6	170	180	175	175	170
12	175	170	180	180	180
18	175	170	180	180	175
24	175	160	180	175	175
30	170	165	175	175	180
36	175	165	175	180	180
42	170	165	175	175	180
48	165	165	175	185	175

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 4
4/82

	TUBE NUMBER				
Inches From Top	1	2	3	4	5
0	185	165	175	175	180
6	180	170	175	170	175
12	180	175	180	175	175
18	185	175	180	175	175
24	190	180	180	180	185
30	185	180	175	175	185
36	185	185	170	180	185
42	175	185	170	175	185
48	185	175	170	175	180

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 1
11/82

Inches From Top	TUBE NUMBER 1	2	3	4	5
0	179.7	175.0	173.4	163.3	174.6
6	171.2	175.2	173.4	172.2	170.5
12	178.9	170.2	174.8	170.2	173.9
18	167.2	170.3	163.6	172.2	173.9
24	176.2	176.9	173.6	170.8	173.1
30	165.5	167.3	173.7	165.7	172.6
36	160.8	166.5	169.4	159.5	167.4
42	156.8	162.1	174.0	167.3	169.2
48	167.3	165.8	171.6	160.4	177.3

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 2
11/82

Inches From Top	TUBE NUMBER 1	2	3	4	5
0	174.2	173.2	172.0	174.3	177.1
6	175.4	172.5	175.4	175.9	176.8
12	176.6	167.9	177.2	174.4	168.8
18	175.7	166.8	177.9	177.3	175.6
24	179.5	163.6	178.5	174.6	176.4
30	175.0	160.9	172.8	174.8	176.9
36	175.9	153.5	176.6	174.8	174.1
42	170.4	166.7	172.9	172.1	167.6
48	170.4	169.0	169.2	171.5	168.2

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 3
11/82

	TUBE NUMBER				
Inches From Top	**1**	**2**	**3**	**4**	**5**
0	167.5	174.2	174.2	181.8	175.6
6	159.6	173.7	174.4	179.0	169.3
12	169.4	172.4	178.6	178.9	172.3
18	174.6	167.3	178.0	178.8	176.6
24	171.8	166.0	178.7	178.0	173.2
30	168.6	150.5	175.4	175.8	173.5
36	172.6	161.1	173.5	173.5	173.3
42	159.9	160.3	174.3	169.9	179.4
48	161.8	162.9	174.6	175.0	175.4

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TEST PANELS
MEASURED ULTRASONICALLY
TUBEWALL THICKNESS, MILS

Panel No. 4
11/82

Inches From Top	TUBE NUMBER 1	2	3	4	5
0	176.5	162.2	173.0	164.9	167.6
6	168.5	162.6	171.8	170.1	165.3
12	177.0	166.4	178.7	172.6	169.9
18	179.2	171.5	172.2	178.4	170.7
24	172.3	175.3	174.0	178.4	177.4
30	177.4	176.8	173.2	176.6	178.9
36	177.9	173.6	169.1	179.8	181.7
42	175.5	171.6	172.2	173.6	179.4
48	176.9	168.2	163.0	174.2	176.5

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
NORTH OR LEFT WALL LEVEL 1
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE 5/80	5/81	4/82	11/82	4/84
1	175.0	170.0	165.0	159.4	159.6
3	170.0				
5	175.0	170.0	165.0	158.6	162.6
7	170.0				
9	170.0	165.0	165.0	159.5	157.1
11	165.0				
13	170.0	170.0	165.0	162.6	159.3
15	165.0				
17	165.0	165.0	160.0	155.9	153.4
19	175.0				
21	175.0	165.0	165.0	162.8	156.9
23	185.0				
25	190.0	165.0	160.0	155.8	153.2
27	175.0				
29	165.0	165.0	165.0	159.2	156.9
31	170.0				
33	170.0	170.0	170.0	163.4	170.9
35	165.0				
37	175.0	170.0	165.0	153.5	161.3
39	170.0				
41	170.0	165.0	160.0	158.4	157.1
43	170.0				
45	175.0	170.0	165.0	159.2	167.0
47	170.0				
49	170.0	165.0	165.0	153.6	158.8
51	175.0				
53	170.0	165.0	165.0	154.3	161.5
55	175.0				
57	175.0	170.0	165.0	158.6	163.5
59	175.0				
61	170.0	165.0	160.0	159.6	158.8
63	170.0				
65	170.0	170.0	165.0	159.0	156.5
67	180.0				
69	175.0	170.0	170.0	164.0	160.2
71	180.0				
73	170.0	170.0	165.0	158.4	168.3
75	175.0				
76			165.0	156.8	165.8

TUBE # 1 IS AT THE NORTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
NORTH OR LEFT WALL LEVEL 2
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	165.0	165.0	165.0	162.4	162.8
3	160.0				
5	155.0	170.0	165.0	162.2	161.4
7	160.0				
9	160.0	170.0	165.0	156.9	162.0
11	160.0				
13	155.0	170.0	165.0	158.6	160.3
15	160.0				
17	160.0	165.0	160.0	152.5	157.0
19	160.0				
21	155.0	170.0	180.0	174.7	
23	175.0				
25	180.0	170.0	175.0	169.4	
27	170.0				
29	160.0	165.0	160.0	155.2	155.4
31	170.0				
33	160.0	170.0	165.0	158.9	163.6
35	160.0				
37	165.0	170.0	175.0	162.4	167.2
39	160.0				
41	165.0	165.0	165.0	152.6	161.0
43	155.0				
45	155.0	170.0	170.0	163.3	165.6
47	160.0				
49	155.0	165.0	170.0	157.6	160.1
51	155.0				
53	155.0	170.0	165.0	160.0	164.9
55	160.0				
57	155.0	170.0	170.0	164.8	167.7
59	160.0				
61	160.0	165.0	165.0	157.5	161.4
63	155.0				
65	155.0	170.0	170.0	156.8	160.1
67	155.0				
69	160.0	170.0	170.0	162.8	165.8
71	160.0				
73	160.0	165.0	165.0	162.8	175.0
75	160.0				
76			165.0	163.0	169.1

TUBE # 1 IS AT THE NORTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
NORTH OR LEFT WALL LEVEL 3
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	175.0	165.0	163.4	169.9
3	165.0				
5	170.0	165.0			
7	170.0				
9	175.0	165.0	160.0	157.7	161.2
11	165.0				
13	170.0	170.0	165.0		161.3
15	165.0				
17	165.0	175.0	165.0	163.5	162.1
19	170.0				
21	170.0	165.0	165.0	165.7	
23	165.0				
25	170.0	170.0	160.0	154.4	
27	180.0				
29	185.0	180.0	160.0	162.0	159.3
31	180.0				
33	180.0	175.0	165.0	160.4	157.9
35	175.0				
37	170.0	180.0	165.0		160.2
39	170.0				
41	170.0	165.0	160.0	158.1	163.9
43	165.0				
45	165.0	170.0	165.0	162.3	164.9
47	160.0				
49	160.0	165.0	165.0	159.3	162.6
51	160.0				
53	165.0	170.0	165.0	157.2	165.0
55	165.0				
57	170.0	175.0	170.0	162.0	165.6
59	165.0				
61	165.0	170.0	165.0	157.7	162.2
63	165.0				
65	160.0	160.0	165.0	158.0	164.3
67	160.0				
69	155.0	170.0	165.0	161.6	164.8
71	150.0				
73	165.0	175.0	165.0	161.8	167.2
75	175.0				
76			165.0	161.9	162.4

TUBE # 1 IS AT THE NORTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
NORTH OR LEFT WALL LEVEL 4
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	175.0	165.0	165.0	161.6	166.1
3	170.0				
5	165.0	165.0	170.0	164.0	157.0
7	165.0				
9	170.0	165.0	165.0	163.7	160.1
11	165.0				
13	165.0	165.0	170.0	161.9	162.8
15	165.0				
17	180.0	165.0	170.0	162.7	165.2
19	170.0				
21	170.0	160.0	165.0	159.0	164.1
23	165.0				
25	180.0	180.0	180.0	182.9	184.9
27	165.0				
29	170.0	175.0	165.0	163.9	165.8
31	170.0				
33	175.0	170.0	165.0	159.3	162.3
35	175.0				
37	170.0	170.0	165.0	167.4	
39	180.0				
41	185.0	180.0	180.0	172.4	174.3
43	165.0				
45	180.0	180.0	175.0	182.6	180.1
47	180.0				
49	165.0	160.0	165.0	161.6	170.8
51	155.0				
53	155.0	155.0	175.0	172.3	157.1
55	165.0				
57	170.0	170.0	165.0	162.5	165.7
59	165.0				
61	165.0	165.0	165.0	158.4	164.7
63	160.0				
65	160.0	155.0	165.0	154.9	164.6
67	160.0				
69	160.0	160.0	165.0	164.1	163.8
71	165.0				
73	165.0	160.0	170.0	159.2	165.1
75	165.0				
76			165.0	155.7	157.1

TUBE # 1 IS AT THE NORTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
NORTH OR LEFT WALL LEVEL 5
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	175.0	170.0	165.0	162.3	164.8
3	170.0				
5	170.0	145.0	165.0	164.9	163.5
7	170.0				
9	170.0	160.0	165.0	160.2	173.1
11	165.0				
13	165.0	155.0	165.0	159.9	162.1
15	170.0				
17	170.0	160.0	170.0	160.5	163.0
19	175.0				
21	175.0	165.0	165.0	162.3	166.4
23	175.0				
25	180.0	170.0	175.0	174.7	180.6
27	165.0				
29	170.0	160.0	165.0	164.7	178.8
31	170.0				
33	170.0	160.0	160.0	159.3	170.9
35	175.0				
37	170.0	155.0	165.0	161.5	179.5
39	175.0				
41	180.0	175.0	175.0	177.0	178.8
43	170.0				
45	185.0	175.0	180.0	178.5	180.4
47	185.0				
49	170.0	160.0	165.0	161.3	167.9
51	175.0				
53	175.0	160.0	170.0	164.7	168.3
55	170.0				
57	170.0	155.0	160.0	157.1	157.7
59	165.0				
61	175.0	165.0	160.0	160.6	164.3
63	165.0				
65	165.0	160.0	160.0	156.2	160.2
67	170.0				
69	165.0	165.0	170.0	158.8	165.8
71	175.0				
73	165.0	165.0	165.0	157.2	165.1
75	165.0				
76			165.0	156.2	173.6

TUBE # 1 IS AT THE NORTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
NORTH OR LEFT WALL LEVEL 6
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	180.0	170.0	165.0		162.3
3	170.0				
5	170.0	170.0	165.0	164.0	167.5
7	160.0				
9	160.0	165.0	165.0	159.0	160.9
11	170.0				
13	165.0	165.0	165.0	157.7	158.4
15	170.0				
17	175.0	165.0	170.0	161.5	161.8
19	165.0				
21	170.0	160.0	165.0	162.7	172.8
23	170.0				
25	170.0	175.0	175.0	176.3	175.5
27	170.0				
29	175.0	165.0	170.0	169.4	169.4
31	185.0				
33	170.0	160.0	165.0	160.3	161.3
35	175.0				
37	170.0	160.0	160.0	161.3	159.2
39	170.0				
41	165.0	175.0	175.0	166.7	176.2
43	175.0				
45	190.0	180.0	180.0	175.6	177.0
47	185.0				
49	185.0	160.0	165.0	159.0	162.9
51	165.0				
53	165.0	165.0	165.0	164.0	165.9
55	160.0				
57	165.0	165.0	165.0	159.1	160.6
59	170.0				
61	180.0	160.0	165.0	162.2	162.1
63	180.0				
65	170.0	160.0	165.0	156.8	158.1
67	170.0				
69	165.0	160.0	160.0	159.3	157.1
71	175.0				
73	170.0	160.0	165.0	153.7	159.4
75	170.0				
76			165.0	159.7	158.8

TUBE # 1 IS AT THE NORTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
SOUTH WALL LEVEL 1
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	190.0	170.0	164.0	160.3
3	170.0				
5	175.0	170.0	160.0	161.3	158.2
7	170.0				
9	175.0	165.0	170.0	171.4	162.5
11	170.0				
13	170.0	170.0	165.0	166.3	165.7
15	170.0				
17	165.0	165.0	160.0	156.5	157.8
19	170.0				
21	175.0	170.0	165.0	159.9	163.9
23	175.0				
25	170.0	170.0	160.0	160.1	155.0
27	170.0				
29	175.0	175.0	165.0	158.5	158.6
31	170.0				
33	175.0	180.0	165.0	159.4	161.2
35	175.0				
37	175.0	180.0	170.0	160.2	163.9
39	170.0				
41	170.0	175.0	165.0	168.0	159.1
43	170.0				
45	175.0	175.0	165.0	167.4	166.2
47	170.0				
49	170.0	175.0	165.0	152.8	164.4
51	175.0				
53	175.0	175.0	165.0	159.8	166.3
55	170.0				
57	170.0	180.0	160.0	153.0	160.6
59	170.0				
61	170.0	175.0	155.0	157.9	160.6
63	165.0				
65	170.0	180.0	160.0	166.1	162.5
67	175.0				
69	165.0	180.0	165.0	156.3	160.8
71	170.0				
73	170.0	175.0	165.0	151.3	163.4
75	165.0				
76			160.0	152.0	156.9

TUBE # 1 IS AT THE SOUTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
SOUTH OR RIGHT WALL LEVEL 2
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	175.0	170.0	158.8	159.8
3	170.0				
5	165.0	170.0	165.0	155.9	155.0
7	175.0				
9	170.0	175.0	165.0	165.0	164.7
11	165.0				
13	170.0	175.0	170.0	163.0	157.9
15	170.0				
17	165.0	175.0	160.0	155.6	154.3
19	165.0				
21	170.0	180.0	165.0	160.2	162.0
23	170.0				
25	170.0	170.0	165.0	158.3	158.9
27	165.0				
29	170.0	175.0	170.0	161.4	160.2
31	170.0				
33	175.0	180.0	170.0	164.4	164.3
35	175.0				
37	175.0	185.0	185.0	166.9	
39	175.0				
41	175.0	180.6	180.0	169.5	
43	175.0				
45	180.0	185.0	170.0	168.2	159.3
47	185.0				
49	170.0	175.0	165.0	167.2	157.3
51	175.0				
53	185.0	180.0	175.0	171.9	165.0
55	175.0				
57	165.0	180.0	170.0	157.3	162.1
59	185.0				
61	170.0	175.0	165.0	160.4	159.7
63	185.0				
65	185.0	180.0	160.0	161.0	162.1
67	170.0				
69	170.0	185.0	170.0	161.2	164.7
71	170.0				
73	165.0	180.0	160.0	154.6	159.8
75	170.0				
76			160.0	158.2	159.9

TUBE # 1 IS AT THE SOUTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
SOUTH OR RIGHT WALL LEVEL 3
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	170.0	165.0	157.3	161.5
3	165.0				
5	185.0	160.0			156.0
7	170.0				
9	175.0	170.0	170.0	163.2	168.8
11	185.0				
13	175.0	200.0	165.0	165.8	166.0
15	165.0				
17	170.0	190.0	165.0	157.2	159.9
19	170.0				
21	165.0	180.0	165.0	163.3	164.8
23	165.0				
25	165.0	170.0	165.0	162.5	161.5
27	165.0				
29	170.0	185.0	170.0	167.6	169.1
31	170.0				
33	175.0	180.0	175.0	167.0	168.8
35	170.0				
37	180.0	175.0	165.0	169.7	170.7
39	180.0				
41	170.0	195.0	165.0	162.2	169.3
43	165.0				
45	175.0	170.0	170.0	165.0	173.4
47	190.0				
49	185.0	175.0	145.0		154.2
51	180.0				
53	190.0	175.0	160.0	153.6	157.7
55	195.0				
57	205.0	175.0	155.0	142.7	162.5
59	205.0				
61		170.0	155.0	140.3	165.0
63	185.0				
65	185.0	170.0	165.0	151.8	163.8
67	190.0				
69	180.0	170.0	165.0	161.2	164.6
71	175.0				
73	170.0	170.0	165.0	157.7	156.6
75	165.0				
76			160.0		159.1

TUBE # 1 IS AT THE SOUTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
SOUTH OR RIGHT WALL LEVEL 4
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	160.0	150.0	165.0	163.5	157.5
3	160.0				
5	165.0	150.0	165.0	165.8	162.1
7	165.0				
9	170.0	160.0	165.0	163.6	160.4
11	165.0				
13	165.0	180.0	175.0	163.0	162.4
15	165.0				
17	180.0	170.0	165.0	159.3	162.2
19	165.0				
21	170.0	175.0	170.0	164.8	163.5
23	170.0				
25	165.0	150.0	165.0	159.3	160.5
27	170.0				
29	175.0	155.0	165.0	158.3	157.8
31	190.0				
33	170.0	155.0	165.0	169.6	154.7
35	165.0				
37	175.0	155.0	170.0	161.3	162.7
39	170.0				
41	180.0	155.0	170.0	160.5	166.4
43	185.0				
45	190.0	155.0	180.0		182.2
47	185.0				
49	190.0	155.0	185.0		188.6
51	165.0				
53	205.0	150.0	200.0		193.1
55	180.0				
57	205.0	145.0	165.0	167.8	166.0
59	185.0				
61	180.0	150.0	160.0	154.5	156.3
63	180.0				
65	175.0	150.0	170.0	167.2	168.9
67	170.0				
69	170.0	130.0	170.0	163.0	163.5
71	170.0				
73	165.0	155.0	165.0	156.7	159.5
75	170.0				
76			160.0	159.5	167.6

TUBE # 1 IS AT THE SOUTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
SOUTH OR RIGHT WALL LEVEL 5
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	155.0	170.0	155.5	157.0
3	180.0				
5	175.0	150.0	160.0	164.4	167.4
7	170.0				
9	165.0	150.0	170.0	155.8	169.6
11	165.0				
13	165.0	160.0	165.0	158.2	164.0
15	165.0				
17	165.0	170.0	165.0	157.7	164.2
19	170.0				
21	170.0	150.0	165.0	160.3	160.6
23	170.0				
25	165.0	190.0	160.0	159.2	160.5
27	170.0				
29	165.0	150.0	165.0	160.1	166.7
31	185.0				
33	170.0	150.0	165.0	168.6	165.8
35	170.0				
37	170.0	155.0	165.0	159.8	163.9
39	170.0				
41	175.0	155.0	170.0	159.4	159.2
43	185.0				
45	170.0	175.0	185.0		191.0
47	165.0				
49	165.0	155.0	180.0	180.0	184.9
51	165.0				
53	225.0	155.0	190.0		192.5
55	165.0				
57	160.0	150.0	165.0	162.8	163.9
59	165.0				
61	170.0	160.0	165.0	161.6	165.3
63	170.0				
65	165.0	150.0	170.0	162.3	166.3
67	170.0				
69	170.0	150.0	165.0	158.8	165.8
71	170.0				
73	170.0	155.0	170.0	161.8	166.4
75	170.0				
76			170.0	162.0	168.2

TUBE # 1 IS AT THE SOUTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
SOUTH OR RIGHT WALL LEVEL 6
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	175.0	155.0	180.0	170.6	173.5
3	165.0				
5	165.0	155.0	165.0	156.9	170.1
7	170.0				
9	170.0	155.0	170.0	161.0	165.2
11	170.0				
13	165.0	160.0	160.0	156.6	166.3
15	165.0				
17	170.0	150.0	170.0	160.8	168.9
19	170.0				
21	170.0	150.0	165.0	166.4	172.9
23	170.0				
25	180.0	160.0	165.0	158.1	175.3
27	165.0				
29	165.0	160.0	170.0	159.2	174.6
31	165.0				
33	165.0	160.0	170.0	162.2	171.4
35	170.0				
37	170.0	165.0	165.0	159.4	171.1
39	185.0				
41	180.0	165.0	165.0	156.3	173.1
43	170.0				
45	185.0	165.0	185.0	183.0	189.2
47	185.0				
49	170.0	170.0	185.0	172.4	188.4
51	165.0				
53	170.0	160.0	160.0	150.9	170.0
55	170.0				
57	170.0	165.0	165.0	158.0	176.5
59	170.0				
61	170.0	170.0	170.0	162.1	175.2
63	165.0				
65	165.0	165.0	170.0	164.9	173.4
67	170.0				
69	170.0	160.0	170.0	159.9	162.4
71	170.0				
73	165.0	170.0	165.0	162.5	176.7
75	165.0				
76			165.0		165.7

TUBE # 1 IS AT THE SOUTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
REAR OR EAST WALL LEVEL 1
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	175.0	200.0	170.0	161.0	166.4
3	175.0				
5	170.0	200.0	165.0	157.6	165.0
7	170.0				
9	175.0	200.0	170.0	161.4	168.9
11	175.0				
13	170.0	200.0	165.0	159.4	153.5
15	175.0				
17	180.0	205.0	170.0	161.7	170.6
19	180.0				
21	175.0	200.0	170.0	157.8	169.2
23	170.0				
25	175.0	205.0	175.0	162.0	176.3
27	175.0				
29	170.0	200.0	175.0	167.6	171.4
31	170.0				
33	175.0	205.0	165.0	161.6	175.8
35	170.0				
37	170.0	200.0	175.0	163.6	170.4
39	175.0				
41	170.0	205.0	170.0	164.0	177.9
43	175.0				
45	175.0	215.0	175.0	162.5	176.8
47	175.0				
49	180.0	225.0	170.0	163.4	167.2
51	170.0				
53	175.0	200.0	165.0	157.4	163.9
55	170.0				
57	170.0	225.0	180.0	161.3	167.3
59	175.0				
60	170.0		175.0	160.6	162.1

TUBE # 1 IS AT THE NORTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
REAR OR EAST WALL LEVEL 2
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	155.0	180.0	160.0	156.3	160.2
3	155.0				
5	150.0	180.0	170.0	159.4	152.4
7	155.0				
9	150.0	195.0	170.0	162.6	154.8
11	150.0				
13	150.0	185.0	165.0	159.8	160.3
15	155.0				
17	160.0	185.0	170.0	163.0	165.3
19	160.0				
21	155.0	185.0	170.0	163.0	165.7
23	150.0				
25	160.0	185.0	170.0	157.6	165.0
27	155.0				
29	160.0	180.0	165.0	158.9	163.7
31	155.0				
33	150.0	180.0	165.0	159.6	169.4
35	150.0				
37	150.0	185.0	165.0	161.4	165.9
39	160.0				
41	160.0	180.0	165.0	162.5	168.8
43	160.0				
45	160.0	180.0	170.0	163.2	163.7
47	155.0				
49	155.0	185.0	165.0	167.9	165.0
51	155.0				
53	150.0	180.0	165.0	153.6	167.4
55	150.0				
57	150.0	190.0	175.0	162.7	164.9
59	150.0				
60	155.0		165.0	154.8	155.4

TUBE # 1 IS AT THE NORTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
REAR OR EAST WALL LEVEL 3
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	160.0	195.0	155.0	140.4	147.0
3	165.0				
5	165.0	200.0	160.0	157.4	157.2
7	160.0				
9	160.0	190.0	165.0	161.8	163.2
11	160.0				
13	165.0	185.0	165.0	159.2	162.8
15	170.0				
17	170.0	175.0	165.0	160.4	161.4
19	165.0				
21	165.0	180.0	170.0	163.8	167.3
23	165.0				
25	160.0	175.0	170.0	159.9	162.1
27	165.0				
29	160.0	175.0	165.0	158.6	167.6
31	165.0				
33	165.0	180.0	165.0	157.6	167.5
35	160.0				
37	155.0	190.0	165.0	161.2	166.5
39	160.0				
41	175.0	170.0	165.0	159.9	167.1
43	170.0				
45	170.0	175.0	170.0	162.1	162.1
47	170.0				
49	175.0	175.0	165.0	158.1	160.6
51	180.0				
53	175.0	170.0	160.0	154.3	164.8
55	175.0				
57	175.0	175.0	170.0	164.5	167.3
59	175.0				
60	175.0		155.0	142.3	152.8

TUBE # 1 IS AT THE NORTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
REAR OR EAST WALL LEVEL 4
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	165.0	160.0	155.0	143.3	141.5
3	165.0				
5	165.0	175.0	165.0	157.8	164.8
7	165.0				
9	165.0	175.0	165.0	162.0	178.6
11	170.0				
13	165.0	180.0	165.0	159.6	161.8
15	165.0				
17	170.0	195.0	165.0	162.3	166.3
19	170.0				
21	165.0	175.0	170.0	162.7	166.3
23	165.0				
25	160.0	180.0	165.0	165.8	164.7
27	165.0				
29	180.0	175.0	165.0	159.5	168.6
31	180.0				
33	165.0	175.0	165.0	160.1	162.2
35	165.0				
37	160.0	180.0	170.0	160.6	157.4
39	175.0				
41	170.0	185.0		163.3	
43	185.0				
45	170.0	185.0	170.0	161.4	168.1
47	165.0				
49	165.0	175.0	165.0	159.7	167.3
51	165.0				
53	160.0	170.0	160.0	154.0	168.6
55	165.0				
57	160.0	180.0	170.0	160.5	173.6
59	160.0				
60			135.0	126.6	128.2

TUBE # 1 IS AT THE NORTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
REAR OR EAST WALL LEVEL 5
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	165.0	160.0	152.3	154.7
3	170.0				
5	180.0	170.0	165.0	156.8	162.8
7	180.0				
9	190.0	170.0	165.0	162.0	172.8
11	190.0				
13	195.0	160.0	165.0	158.6	163.2
15	195.0				
17	195.0	170.0	165.0	162.0	168.3
19	180.0				
21	195.0	170.0	165.0	162.2	168.9
23	185.0				
25	185.0	160.0	165.0	160.4	165.5
27	195.0				
29	195.0	160.0	165.0	159.6	172.4
31	195.0				
33	195.0	155.0	165.0	161.5	165.8
35	185.0				
37	185.0	160.0	160.0	159.5	172.9
39	180.0				
41	195.0	160.0	160.0	161.3	166.6
43	190.0				
45	195.0	160.0	165.0	163.5	174.5
47	185.0				
49	185.0	170.0	160.0	164.7	163.5
51	185.0				
53	175.0	155.0	160.0	153.2	162.2
55	175.0				
57	175.0	160.0	165.0	161.9	164.7
59	170.0				
60			150.0	149.9	157.0

TUBE # 1 IS AT THE NORTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
REAR OR EAST WALL LEVEL 6
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1	170.0	175.0	180.0	152.7	156.7
3	165.0				
5	175.0	180.0	175.0	163.5	167.5
7	175.0				
9	190.0	190.0	190.0	177.9	178.8
11	180.0				
13	175.0	185.0	180.0	159.4	163.3
15	170.0				
17	175.0	185.0	175.0	163.3	166.3
19	170.0				
21	170.0	185.0	175.0	161.6	169.7
23	175.0				
25	175.0	180.0	170.0	164.1	164.4
27	175.0				
29	175.0	190.0	170.0	162.0	172.1
31	170.0				
33	170.0	180.0	175.0	171.1	162.0
35	170.0				
37	175.0	180.0	170.0	166.4	167.6
39	185.0				
41	180.0	180.0	170.0	162.7	161.3
43	180.0				
45	175.0	185.0	165.0	159.1	162.9
47	170.0				
49	165.0	180.0	165.0	158.3	166.8
51	170.0				
53	175.0	180.0	165.0	159.7	158.9
55	165.0				
57	175.0	175.0	170.0	165.8	161.6
59	175.0				
60			165.0	164.5	158.4

TUBE # 1 IS AT THE NORTHEAST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
FRONT OR WEST WALL LEVEL 1
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1		185.0	165.0		174.3
5		180.0	165.0		162.5
9		185.0	170.0		160.1
13		185.0	170.0		164.2
17		195.0	155.0		162.3
21		185.0	160.0		169.1
25		180.0	165.0		166.3
29		185.0	170.0		168.1
33		180.0	165.0		170.8
37		175.0	165.0		168.2
41		185.0	170.0		164.8
45		185.0	160.0		169.8
49		190.0	165.0		167.8
53		185.0	160.0		169.4
57		180.0	165.0		175.0
60			170.0		169.2

TUBE # 1 IS AT THE SOUTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
FRONT OR WEST WALL LEVEL 2
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE 5/80	5/81	4/82	11/82	4/84
1		180.0	165.0		188.2
5		175.0	160.0		157.1
9		180.0	155.0		153.1
13		155.0			151.2
17		155.0			
21		165.0			
25		155.0			
29		160.0	195.0		156.9
33		200.0	160.0		155.5
37		170.0			
41		165.0			
45		165.0			
49		170.0	165.0		159.9
53		170.0	160.0		168.0
57			160.0		159.8
60			190.0		163.5

TUBE # 1 IS AT THE SOUTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
FRONT OR WEST WALL LEVEL 3
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1			185.0		189.8
3					189.8
9		170.0	160.0		
11		170.0			
13		170.0			
27		200.0			
29		200.0	190.0		156.1
33		200.0	165.0		156.9
49		170.0	160.0		162.0
51		170.0			
53		170.0			172.7
60			190.0		188.6

TUBE # 1 IS AT THE SOUTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
FRONT OR WEST WALL LEVEL 4
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE 5/80	5/81	4/82	11/82	4/84
1			190.0		188.1
3					188.1
5			160.0		
9		165.0	160.0		
11		165.0			
13		165.0			
27		200.0	190.0		
29		200.0	190.0		156.8
31		200.0	190.0		
33					156.2
49		170.0			
51		170.0			
53		170.0	160.0		156.3
57			155.0		
60			190.0		185.2

TUBE # 1 IS AT THE SOUTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
FRONT OR WEST WALL LEVEL 5
MEASURED ULTRASONICALLY

TUBE #			DATE OF MEASURE		
	5/80	5/81	4/82	11/82	4/84
1			160.0		177.6
5			165.0		168.5
7		175.0			
9			160.0		161.7
13			160.0		
17			165.0		
19		165.0			
21			165.0		158.4
25			160.0		
29			165.0		
31		165.0			
33			155.0		183.5
37			160.0		
41		170.0	160.0		163.4
45			160.0		
49			165.0		
53		180.0	165.0		165.6
57			170.0		164.3
60			180.0		157.8

TUBE # 1 IS AT THE SOUTHWEST CORNER OF THE UNIT

WIPCO CORROSION STUDY
FIELD MEASUREMENTS OF TUBE WALL THICKNESS, MILS
FRONT OR WEST WALL LEVEL 6
MEASURED ULTRASONICALLY

TUBE #	DATE OF MEASURE				
	5/80	5/81	4/82	11/82	4/84
1		175.0	160.0		175.3
5		180.0	165.0		162.3
9		175.0	165.0		165.3
13		180.0	160.0		160.0
17		170.0	170.0		169.7
21		180.0	165.0		174.4
25		175.0	165.0		173.9
29		180.0	165.0		168.6
33		175.0	170.0		169.5
37		175.0	170.0		162.8
41		170.0	170.0		168.5
45		175.0	165.0		159.3
49		170.0	160.0		172.9
53		175.0	165.0		168.3
57		175.0	165.0		175.1
60			180.0		165.2

PANEL NO. 1

Tube No.	Expo T Mos.	Tube Side	Before After Test	0" (M)	0" (U)	6" (U)	12" (U)	18" (U)	24" (U)	30" (U)	36" (U)	42" (U)	47" (U)	47" (M)	Av Δ
1	0	FS	Before	.178	.179	.180	.175	.174	.173	.172	.170	.169	.168	.168	
	47	FS	After	.179			.176	.172	.172	.170	.168	.169	.172	.170	
		FS	Δ	+.001			+.001	+.002	-.001	-.002	-.002	.00	+.004	+.002	+.0006
	0	CS	Before	.167	.168	.169	.173	.176	.177	.179	.183	.183	.182	.183	
	47	CS	After	.164			.171	.174	.178	.180	.180	.180	.180	.182	
		CS	Δ	-.003			-.002	-.002	+.001	+.001	-.003	-.003	-.002	-.001	-.0016
2	0	FS	Before	.176	.177	.178	.178	.178	.177	.177	.177	.176	.175	.174	
	47	FS	After		.179	.178	.179	.180	.178	.175	.175	.173	.170	.171	
		FS	Δ		+.002	.00	+.001	+.002	+.001	-.002	-.002	-.003	-.005	-.003	-.0009
	0	CS	Before	.171	.173	.172	.172	.173	.173	.175	.175	.176	.178	.179	
	47	CS	After		.175	.171	.171	.172	.173	.173	.172	.176	.181	.179	
		CS	Δ		+.002	-.001	-.001	-.001	.00	-.002	-.003	.00	+.003	.00	-.0003
3	0	FS	Before	.174	.175	.176	.177	.177	.178	.176	.175	.176	.176	.175	
	47	FS	After		.177	.176	.177	.176	.177	.176	.177	.177	.175	.175	
		FS	ℓ		+.002	.00	.00	-.001	-.001	.00	+.002	+.001	-.001	.00	+.0002
	0	CS	Before	.175	.176	.174	.174	.175	.175	.174	.176	.174	.176	.176	
	47	CS	After		.174	.172		.175	.173	.173	.174	.173	.176	.175	
		CS	Δ		-.002	-.002		.00	-.002	-.001	-.002	-.001	.00	-.001	-.0012
4	0	FS	Before	.174	.174	.176	.176	.176	.176	.174	.171	.169	.168	.168	
	47	FS	After		.175	.177	.175	.175	.172	.169	.168	.166	.164	.165	
		FS	Δ		+.001	+.001	-.001	-.001	-.004	-.005	-.003	-.003	-.004	-.003	-.0022
	0	CS	Before	.175	.176	.176	.175	.175	.177	.184	.183	.188	.186	.185	
	47	CS	After		.174	.175	.174	.175	.178	.183	.183	.188	.186	.185	
		CS	Δ		-.002	-.001	-.001	.00	+.001	-.001	.00	.00	.00	.00	-.0004
5	0	FS	Before	.177	.176	.174	.175	.176	.178	.179	.180	.181	.181	.180	
	47	FS	After		.177	.174	.173	.175	.176	.179	.177	.177		.177	
		FS	Δ		+.001	.00	-.002	-.001	-.002	.00	-.003	-.004		-.003	-.0016
	0	CS	Before	.175	.175	.174	.176	.174	.174	.174	.174	.173	.173	.170	
	47	CS	After		.175		.176	.174	.172	.170	.174	.169		.168	
		CS	Δ		.00		.00	.00	-.002	-.004	.00	-.004		-.002	-.0015

Tube Wall Thickness Measurements of Test Panel

PANEL NO. 2

Tube No.	Expo T Mos.	Tube Side	Before After Test	0" (M)	0" (U)	6" (U)	12" (U)	18" (U)	24" (U)	30" (U)	36" (U)	42" (U)	47" (U)	47" (h)	Av Δ
1	0	FS	Before	.175	.174	.175	.176	.177	.179	.180	.180	.179	.177	.175	
	47	FS	After	.173			.178	.177	.175	.177	.178	.177	.173	.170	
		FS	Δ	-.002			+.002	.00	-.004	-.003	-.002	-.002	-.004	-.005	-.0022
	0	CS	Before	.175	.174	.173	.171	.170	.171	.172	.173	.173	.174	.175	
	47	CS	After	.172	.170	.170	.169	.170	.169	.171	.173			.175	
		CS	Δ	-.003	-.004	-.003	-.002	.00	-.002	-.001	.00			.00	-.0017
2	0	FS	Before	.174	.174	.170	.168	.168	.166	.165	.165	.165	.165	.167	
	47	FS	After		.175	.171	.166	.164	.161	.162	.165	.167	.171	.167	
		FS	Δ		+.001	+.001	-.002	-.004	-.005	-.003	.00	+.002	+.006	.00	-.0004
	0	CS	Before	.174	.175	.179	.183	.185	.189	.190	.187	.185	.183	.182	
	47	CS	After		.174	.176	.184	.184	.186	.187	.183	.181	.179	.176	
		CS	Δ		-.001	-.003	+.001	-.001	-.003	-.003	-.004	-.004	-.004	-.006	-.0028
3	0	FS	Before	.174	.174	.175	.176	.176	.177	.178	.176	.175	.175	.175	
	47	FS	After		.174	.175	.177	.176	.177	.177	.175	.176	.176	.175	
		FS	Δ		.00	.00	+.001	.00	.00	-.001	-.001	+.001	+.001	.00	+.0001
	0	CS	Before	.175	.175	.174	.173	.174	.175	.176	.177	.176	.176	.175	
	47	CS	After		.172	.171	.173	.171	.170	.173	.175	.173	.173	.172	
		CS	Δ		-.003	-.003	.00	-.003	-.005	-.003	-.002	-.003	-.003	-.003	-.0028
4	0	FS	Before	.175	.174	.174	.175	.174	.175	.176	.176	.176	.176	.175	
	47	FS	After		.176	.175	.177	.177	.174	.174	.175	.176	.174	.175	
		FS	Δ		+.002	+.001	+.002	+.003	-.001	-.002	-.001	.00	-.002	.00	+.0002
	0	CS	Before	.176	.175	.176	.176	.175	.176	.177	.178	.177	.177	.176	
	47	CS	After		.172	.175	.175	.175	.174	.175	.174	.174	.173	.174	
		CS	Δ		-.003	-.001	-.001	.00	-.002	-.002	-.004	-.003	-.004	-.002	-.0022
5	0	FS	Before	.180	.179	.180	.179	.179	.178	.178	.177	.176	.176	.175	
	47	FS	After		.181	.182	.179	.179	.177	.174	.173	.168		.169	
		FS	Δ		+.002	+.002	.00	.00	-.001	-.004	-.004	-.008		-.006	-.0019
	0	CS	Before	.169	.168	.170	.171	.172	.174	.175	.177	.177	.177	.178	
	47	CS	After		.169	Weld Patch	.168	.168	.170	.173	.174	.174		.176	
		CS	Δ		+.001		-.003	-.004	-.004	-.002	-.003	-.003		-.002	-.0025

Tube Wall Thickness Measurements of Test Panel

PANEL NO. 3

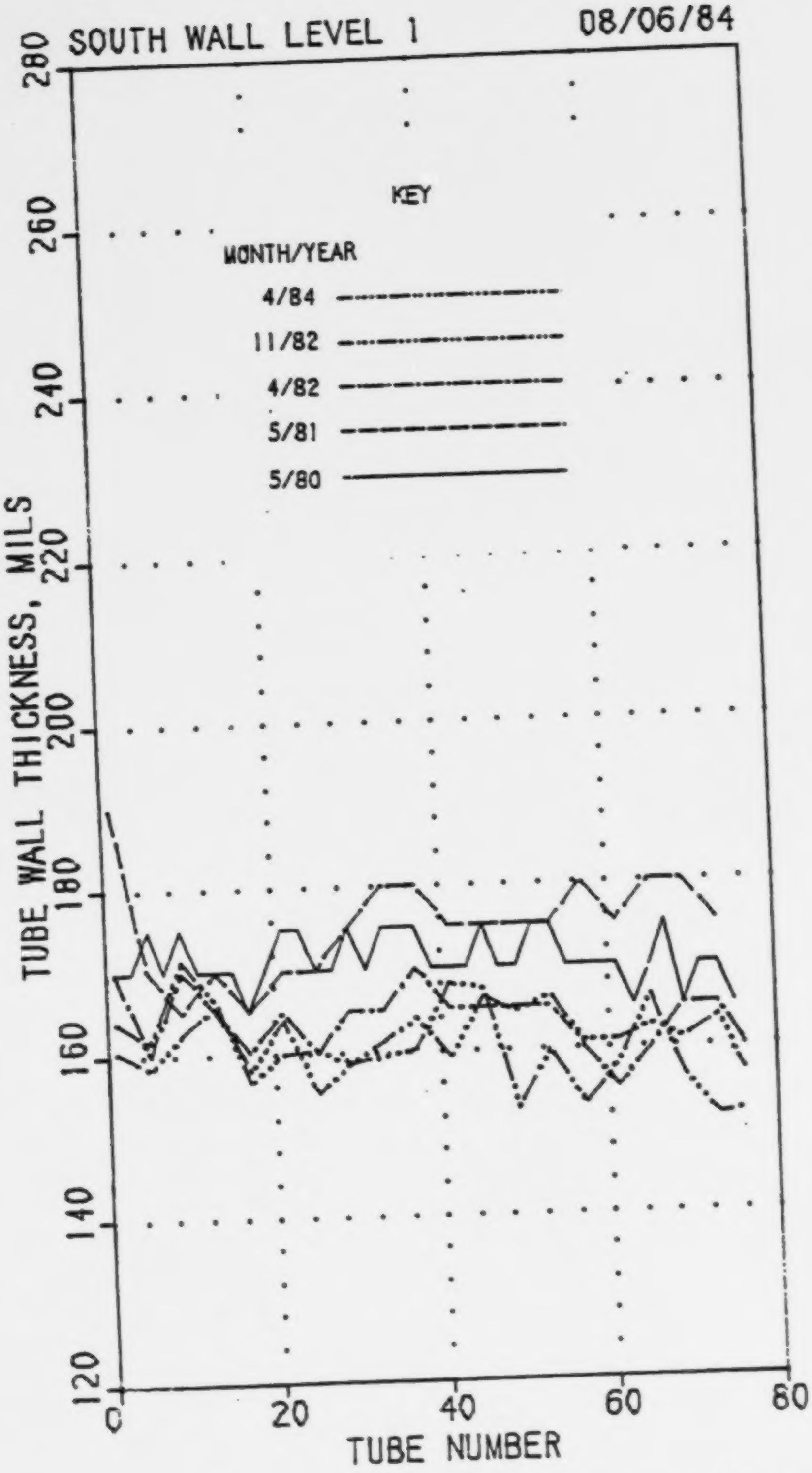
Tube No.	Expo T Mos.	Tube Side	Before After Test	0" (M)	0" (U)	6" (U)	12" (U)	18" (U)	24" (U)	30" (U)	36" (U)	42" (U)	47" (U)	47" (M)	Av Δ
1	0	FS	Before	.175	.174	.173	.174	.175	.174	.173	.172	.171	.170	.171	
	47	FS	After	.167			.173	.175	.174	.173	.171	.171	.171	.169	
		FS	Δ	-.008			-.001	.00	.00	.00	-.001	.00	+.001	-.002	-.0012
	0	CS	Before	.182	.180	.179	.178	.176	.175	.177	.178	.180	.180	.181	
	47	CS	After	.177			.177	.174	.177	.176	.178	.180	.183	.181	
		CS	Δ	-.005			-.001	-.002	+.002	-.001	.00	.00	+.003	.00	-.0004
2	0	FS	Before	.176	.175	.174	.173	.170	.168	.165	.164	.164	.166	.168	
	47	FS	After		.177	.176	.175	.170	.168	.163	.164	.165	.165	.166	
		FS	Δ		+.002	+.002	+.002	.00	.00	-.002	.00	+.001	-.001	-.002	+.0002
	0	CS	Before	.176	.178	.180	.180	.181	.183	.185	.186	.186	.185	.185	
	47	CS	After		.175	.176	.179	.180	.183	.187	.185	.187	.185	.185	
		CS	Δ		-.003	-.004	-.001	-.001	.00	+.002	-.001	+.001	.00	.00	-.0007
3	0	FS	Before	.176	.177	.177	.178	.179	.178	.177	.176	.176	.178	.177	
	47	FS	After		.176	.175	.177	.178	.180	.179	.174	.173	.179	.177	
		FS	Δ		-.001	-.002	-.001	-.001	+.002	+.002	-.002	-.003	+.001	.00	-.0005
	0	CS	Before	.175	.176	.173	.170	.170	.170	.172	.173	.173	.172	.170	
	47	CS	After		.178	.171	.170	.170	.173	.172	.173	.173	.173		
		CS	Δ		+.002	-.002	.00	.00	+.003	.00	.00	.00	+.001		+.0004
4	0	FS	Before	.178	.177	.178	.179	.180	.180	.179	.178	.179	.180	.181	
	47	FS	After		.181	.179	.179	.181	.179	.176	.175	.176	.179	.178	
		FS	Δ		+.004	-.001	.00	+.001	-.001	-.003	-.003	-.003	-.001	-.003	-.001
	0	CS	Before	.171	.170	.171	.172	.171	.170	.171	.173	.173	.173	.172	
	47	CS	After		.169	.168	.169	.169	.170	.171	.173	.173	.174	.172	
		CS	Δ		-.001	-.003	-.003	-.002	.00	.00	.00	.00	+.001	.00	-.0008
5	0	FS	Before	.177	.176	.175	.176	.177	.177	.178	.178	.177	.177	.176	
	47	FS	After		.175	.170	.176	.175	.176	.177	.178	.175		.173	
		FS	Δ		-.001	-.005	.00	-.002	-.001	-.001	.00	-.002		-.003	-.0017
	0	CS	Before	.175	.174	.174	.173	.173	.172	.173	.174	.174	.175	.175	
	47	CS	After		Weld	Weld	.174	.171	.174	.173	.172	.170		.170	
		CS	Δ				+.001	-.002	+.002	.00	-.002	-.004		-.005	-.0014

Tube Wall Thickness Measurements of Test Panel

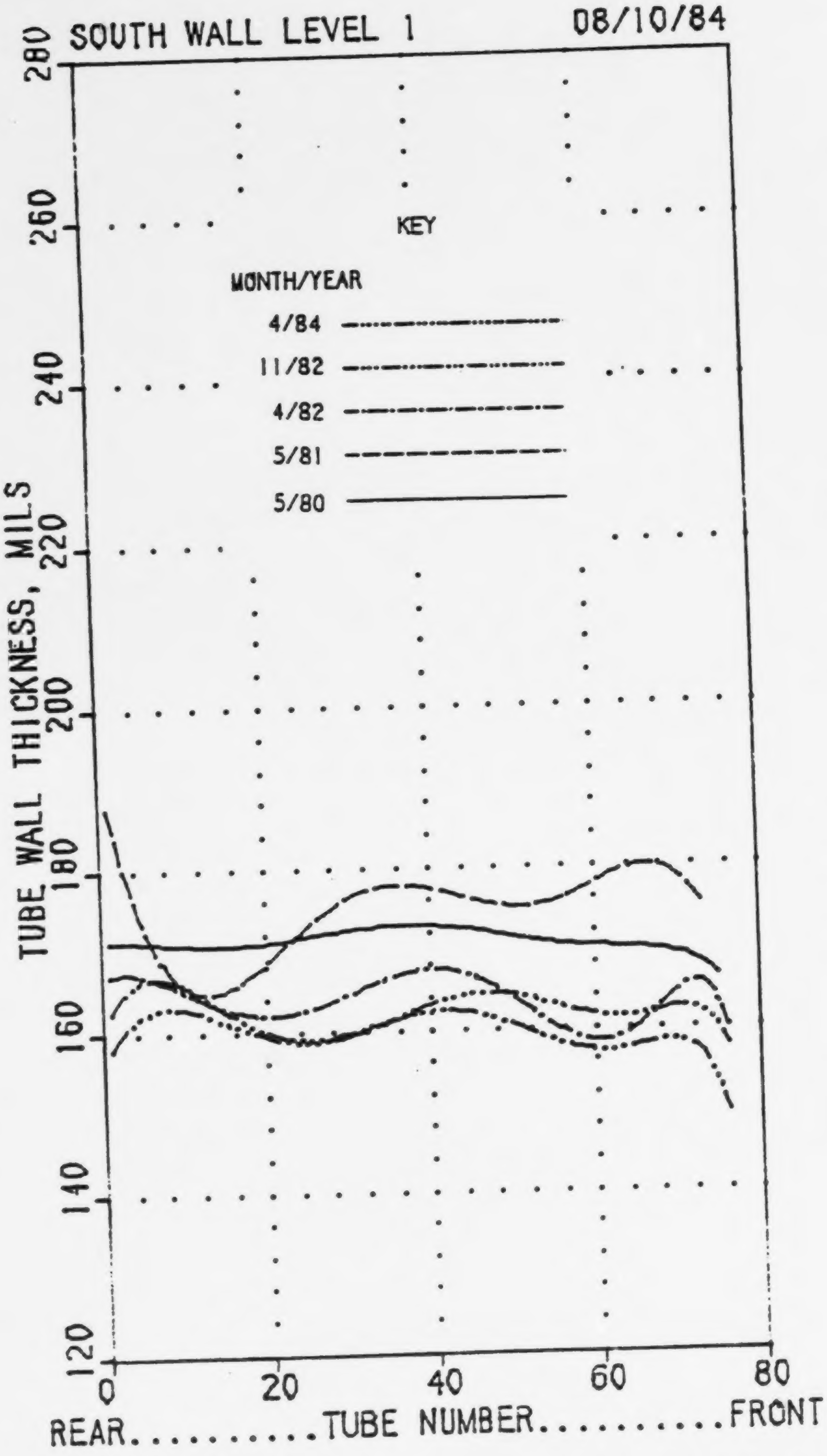
PANEL NO. 4

Tube No.	Expo T Mos.	Tube Side	Before After Test	0" (M)	0" (U)	6" (U)	12" (U)	18" (U)	24" (U)	30" (U)	36" (U)	42" (U)	47" (U)	47" (M)	Av Δ
1	0	FS	Before	.179	.178	.178	.177	.178	.178	.179	.180	.179	.178	.179	
	47	FS	After	.176			.179	.182	.178	.177	.179	.177	.179	.180	
		FS	Δ	-.003			+.002	+.004	.00	-.002	-.001	-.002	+.001	+.001	.00
	0	CS	Before	.175	.174	.173	.174	.175	.174	.173	.172	.171	.169	.170	
	47	CS	After	.170			.175	.172	.172	.170	.171	.171	.170	.166	
		CS	Δ	-.005			+.001	-.003	-.002	-.003	-.001	.00	+.001	-.004	-.0017
2	0	FS	Before	.169	.168	.170	.172	.174	.175	.175	.174	.175	.174	.174	
	47	FS	After		.165	.167	.167	.172	.174	.178	.177	.172	.172	.174	
		FS	Δ		-.003	-.003	-.005	-.002	-.001	+.003	+.003	-.003	-.002	.00	-.0013
	0	CS	Before	.189	.190	.189	.187	.185	.182	.179	.178	.177	.175	.175	
	47	CS	After		.187	.187	.183	.179	.176	.176	.177	.175	.173	.175	
		CS	Δ		-.003	-.002	-.004	-.006	-.006	-.003	-.001	-.002	+.003	.00	-.0024
3	0	FS	Before	.176	.176	.176	.177	.176	.176	.175	.175	.175	.174	.175	
	47	FS	After		.172	.172	.180	.174	.179	.176	.171	.170	.170	.168	
		FS	Δ		-.004	-.004	+.003	-.002	+.003	+.001	-.004	-.005	-.004	-.007	-.0023
	0	CS	Before	.176	.177	.176	.175	.176	.175	.174	.174	.176	.177	.176	
	47	CS	After		.176	.177	.171	.175	.175	.175	.179	.178	.183	.176	
		CS	Δ		-.001	+.001	-.004	-.001	.00	+.001	+.005	+.002	+.006	.00	+.0009
4	0	FS	Before	.176	.177	.178	.179	.180	.180	.182	.180	.179	.178	.178	
	47	FS	After		.173	.172	.179	.180	.182	.180	.179	.178	.175	.175	
		FS	Δ		-.004	-.006	.00	.00	+.002	-.002	-.001	-.001	-.003	-.003	-.0018
	0	CS	Before	.176	.178	.177	.175	.176	.175	.174	.174	.175	.176	.177	
	47	CS	After		.181	.178	.174	.174	.166	.168	.170	.172	.177	.175	
		CS	Δ		+.003	+.001	-.001	-.002	-.009	-.008	-.004	-.003	+.001	-.002	-.0024
5	0	FS	Before	.175	.176	.178	.179	.180	.182	.181	.181	.180	.180	.179	
	47	FS	After		.171	.172	.172	.170	.177	.183	.182	.180		.176	
		FS	Δ		-.005	-.006	-.007	-.010	-.005	+.002	+.001	.00		-.003	-.0037
	0	CS	Before	.180	.179	.179	.176	.175	.174	.174	.174	.175	.174	.175	
	47	CS	After		.177		.177	.176	.173	.170	.167	.166		.168	
		CS	Δ		-.002		+.001	+.001	-.001	-.004	-.007	-.009		-.007	-.0035

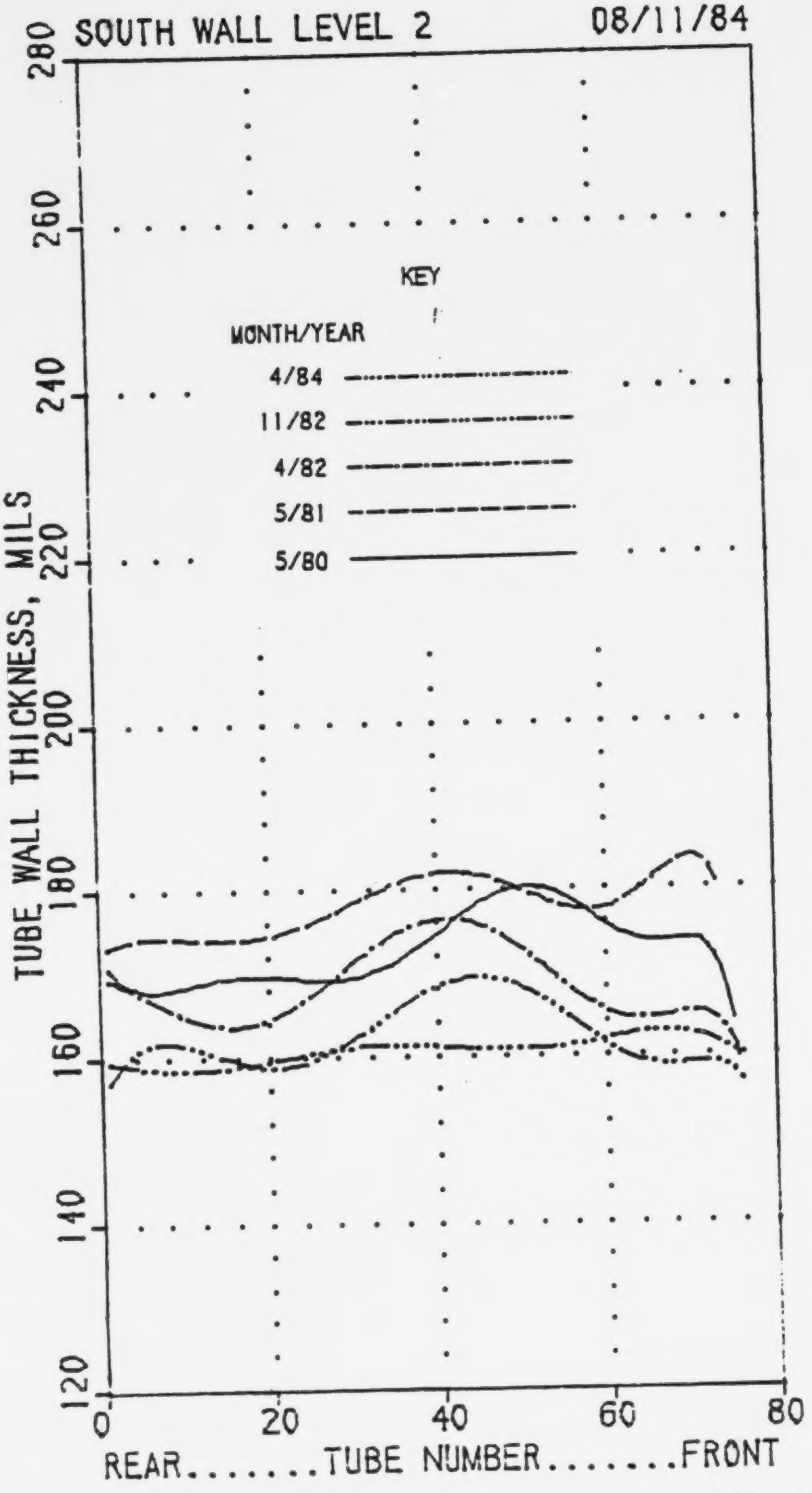
Tube Wall Thickness Measurements of Test Panel



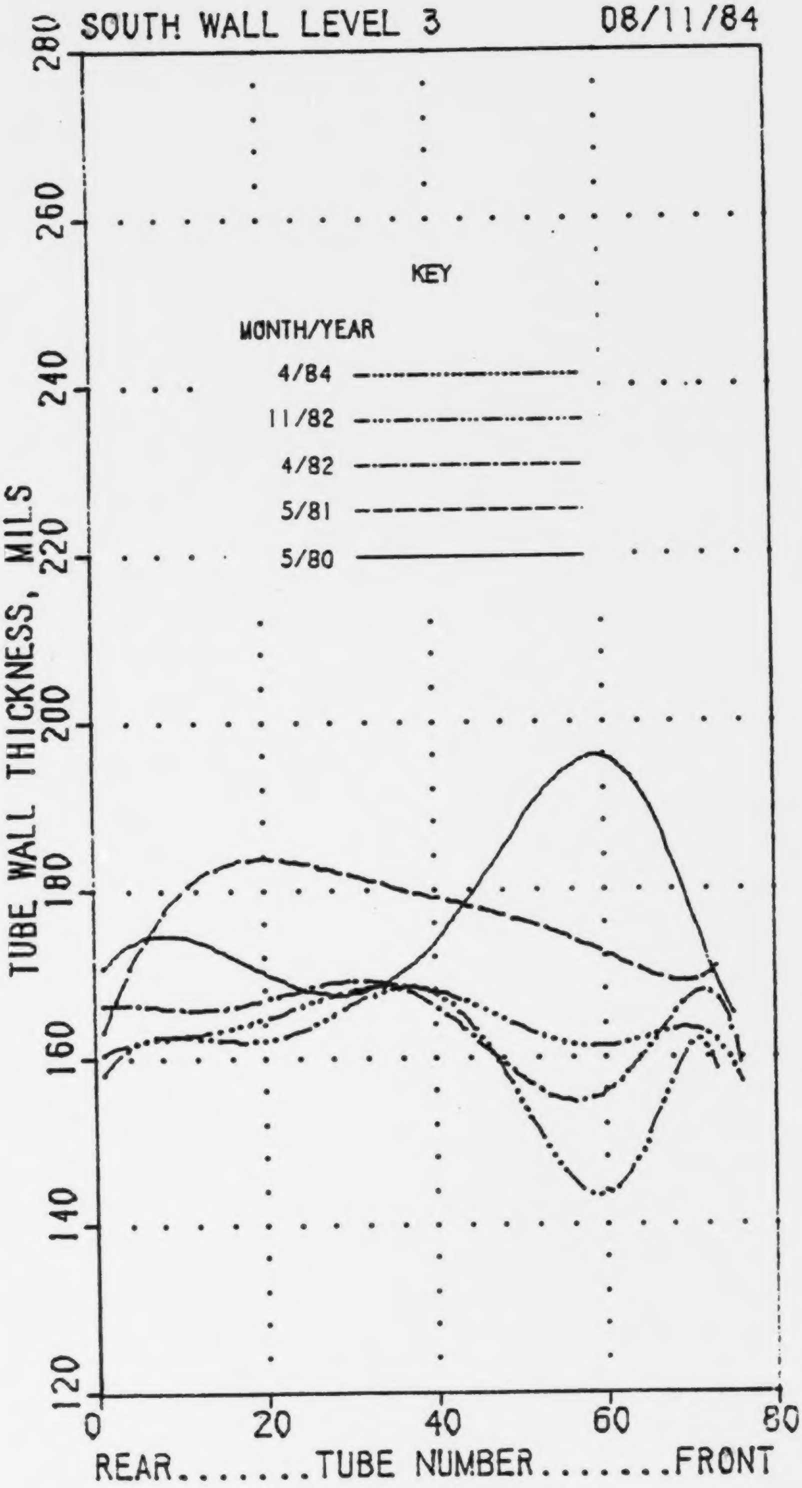
Tube Wall Thickness History, South Wall, Level 1 (Raw Data)



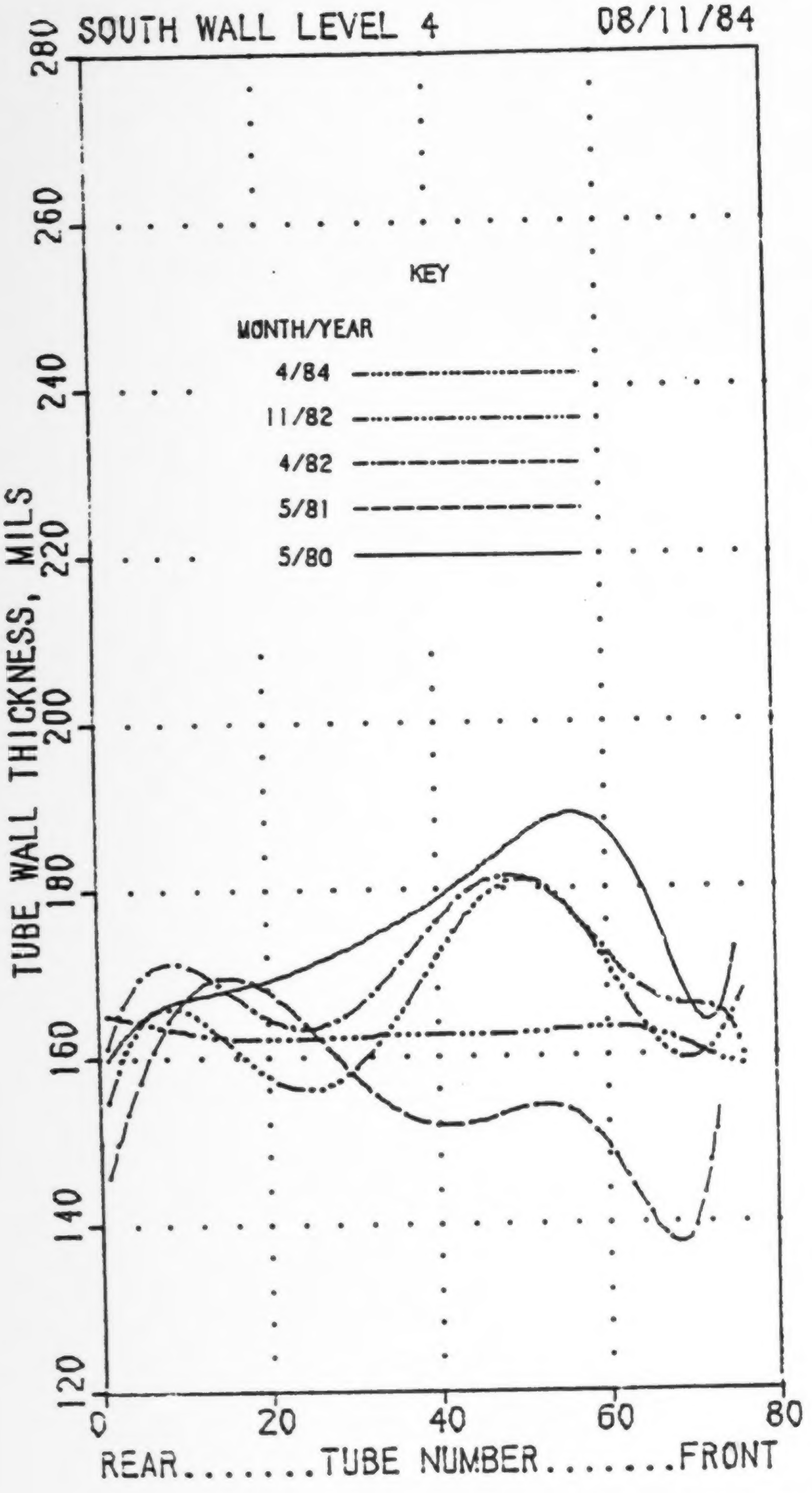
Tube Wall Thickness History, South Wall, Level 1 (Smoothed Form)



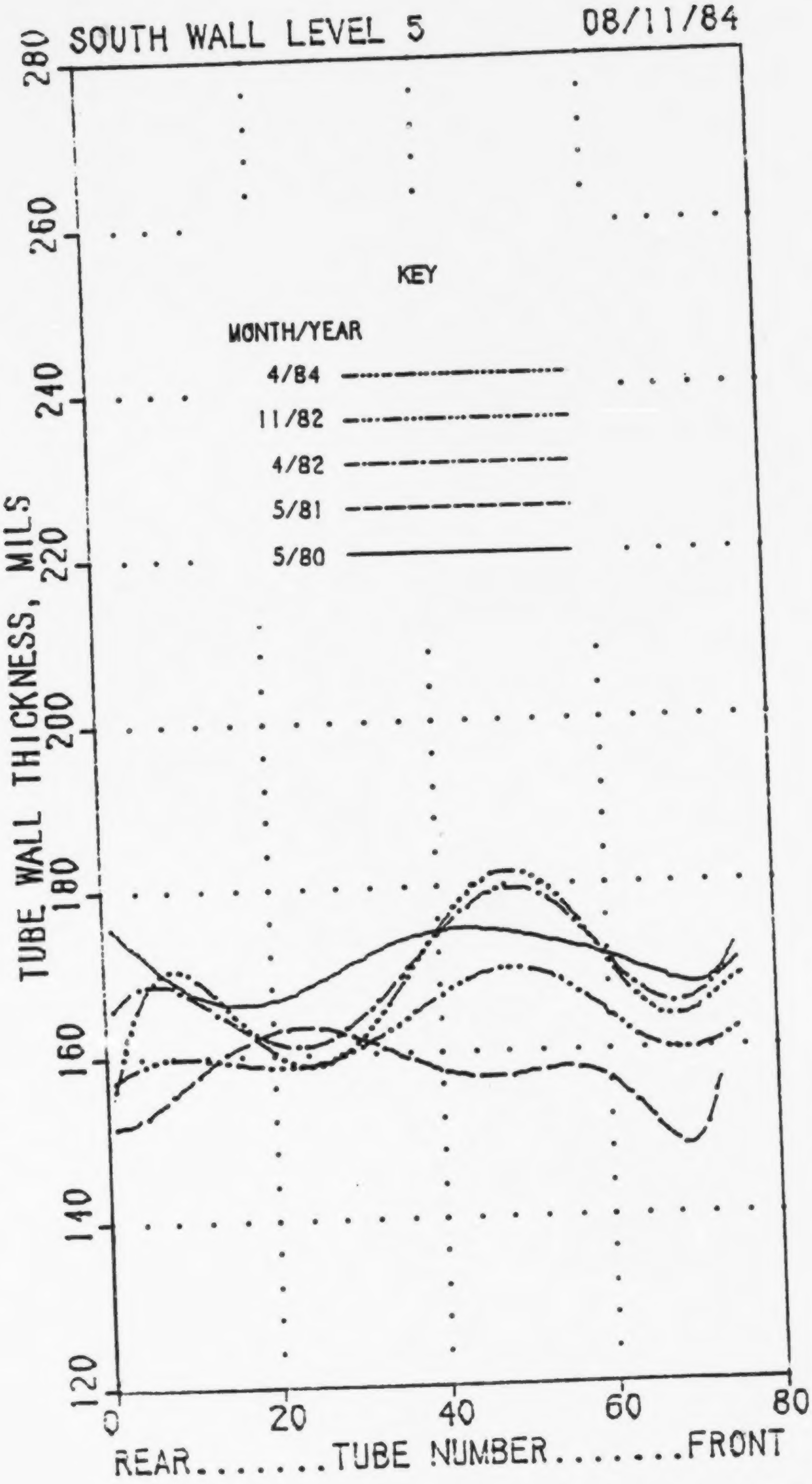
Tube Wall Thickness History, South Wall, Level 2 (Smoothed Form)



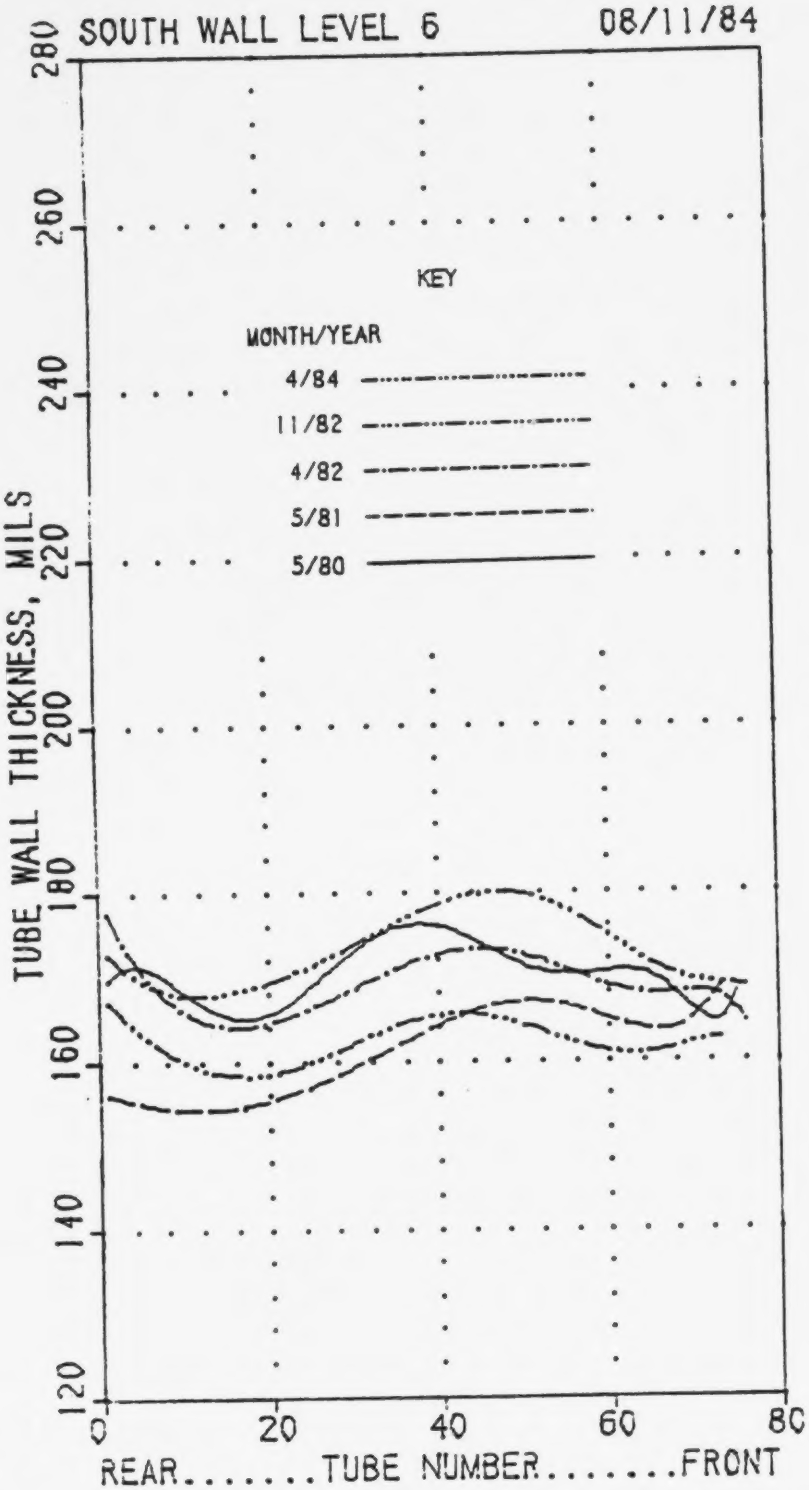
Tube Wall Thickness History, South Wall, Level 3 (Smoothed Form)



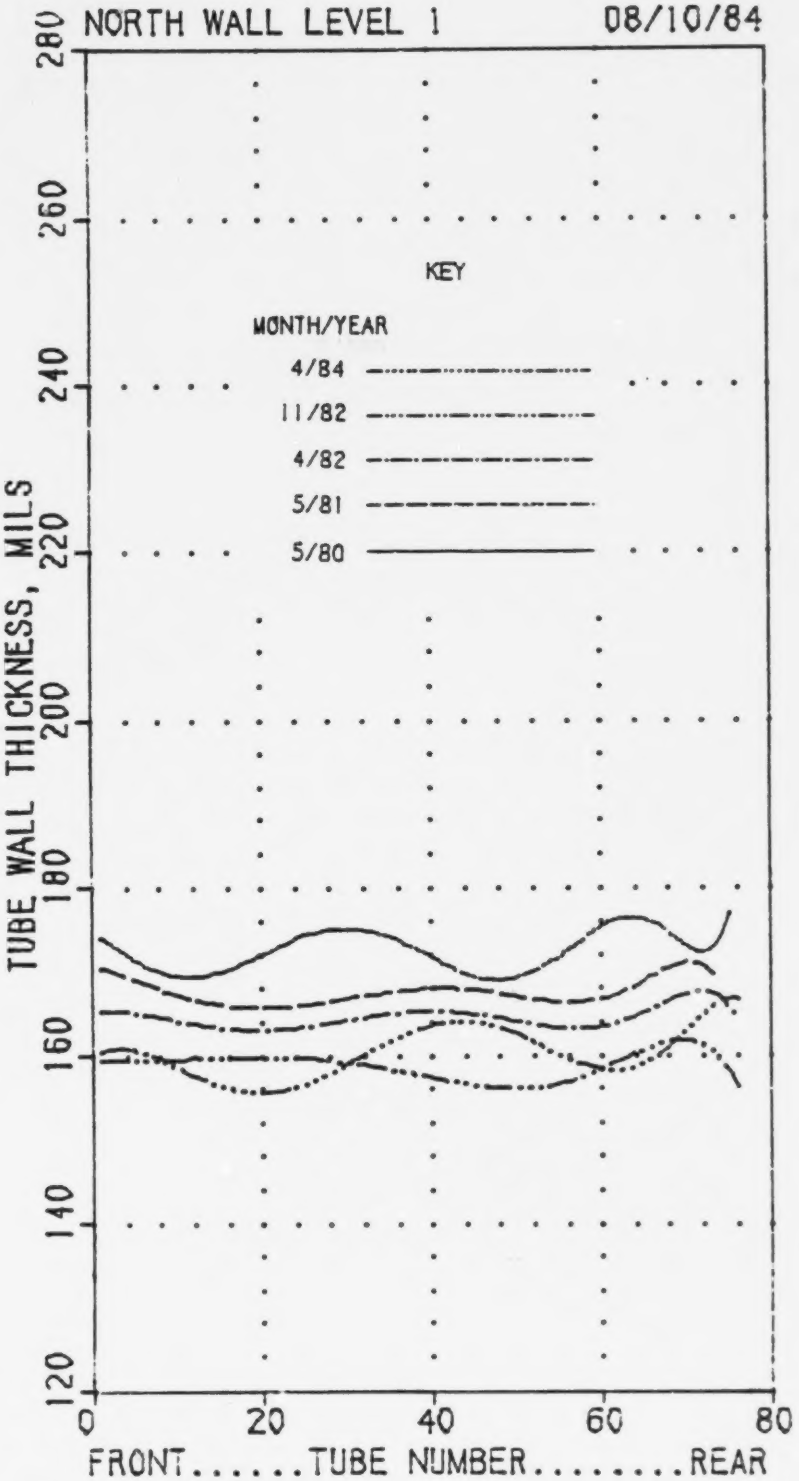
Tube Wall Thickness History, South Wall, Level 4 (Smoothed Form)



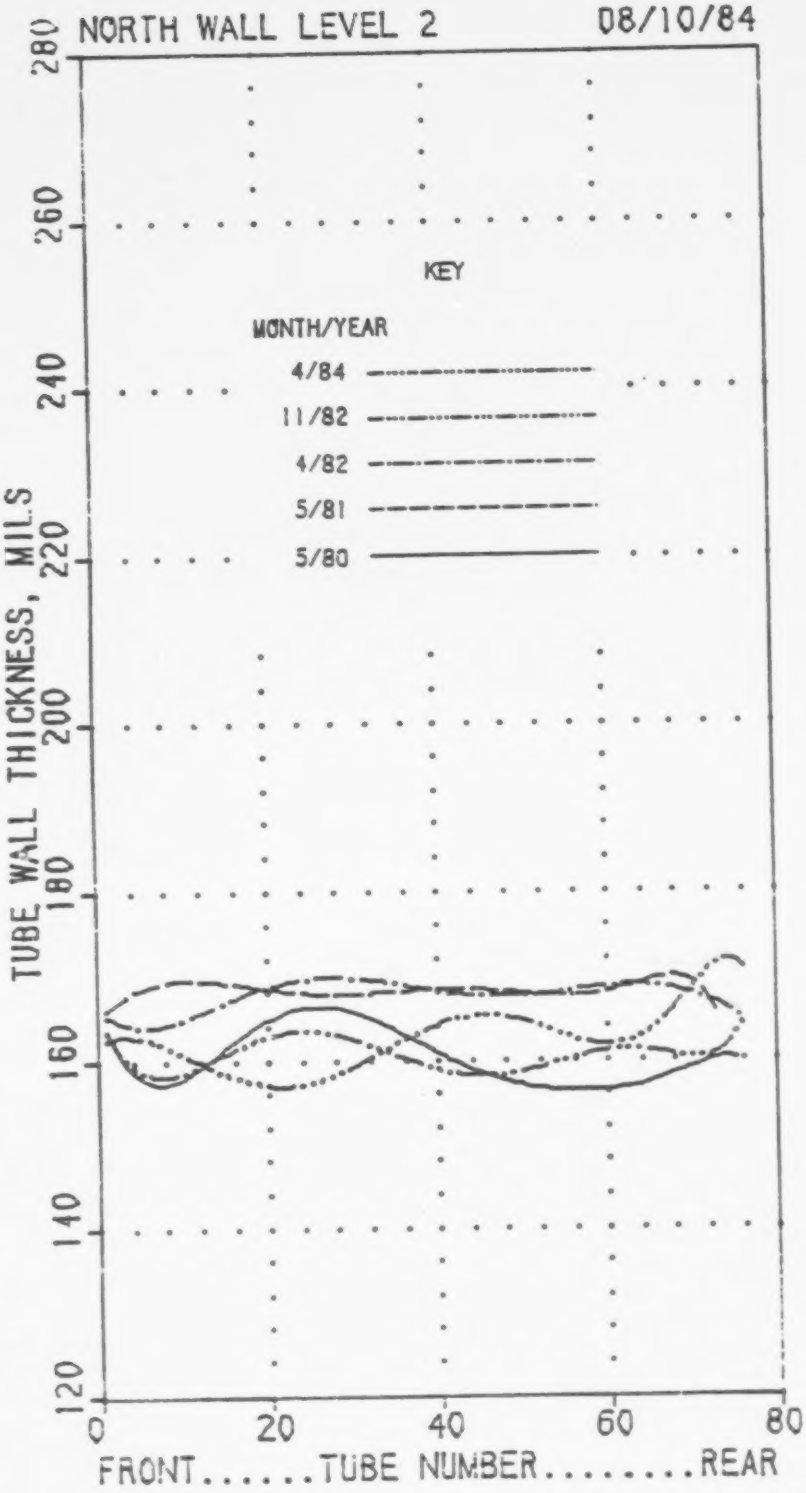
Tube Wall Thickness Histroy, South Wall, Level 5 (Smoothed Form)



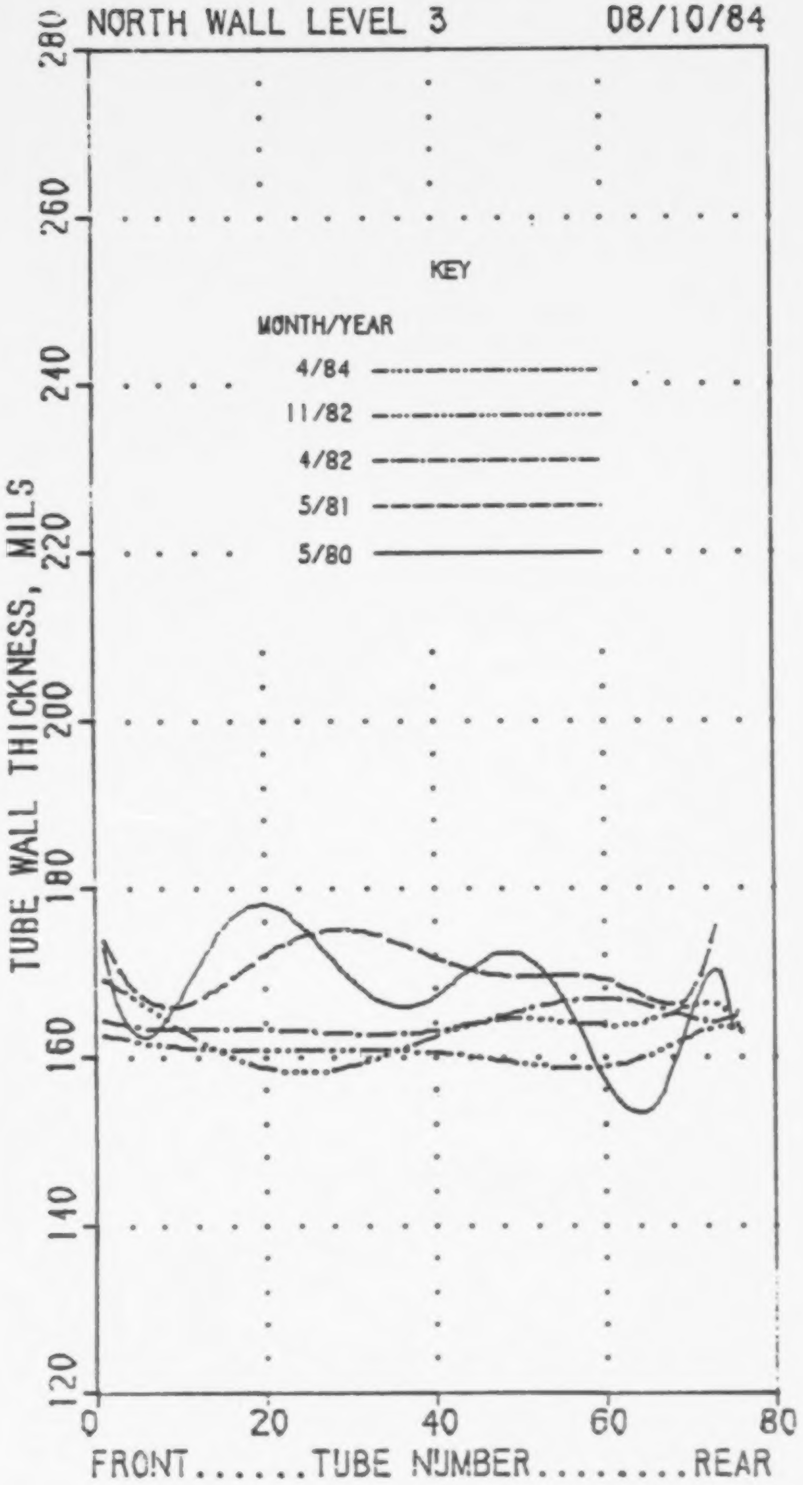
Tube Wall Thickness History, South Wall, Level 6 (Smoothed Form)



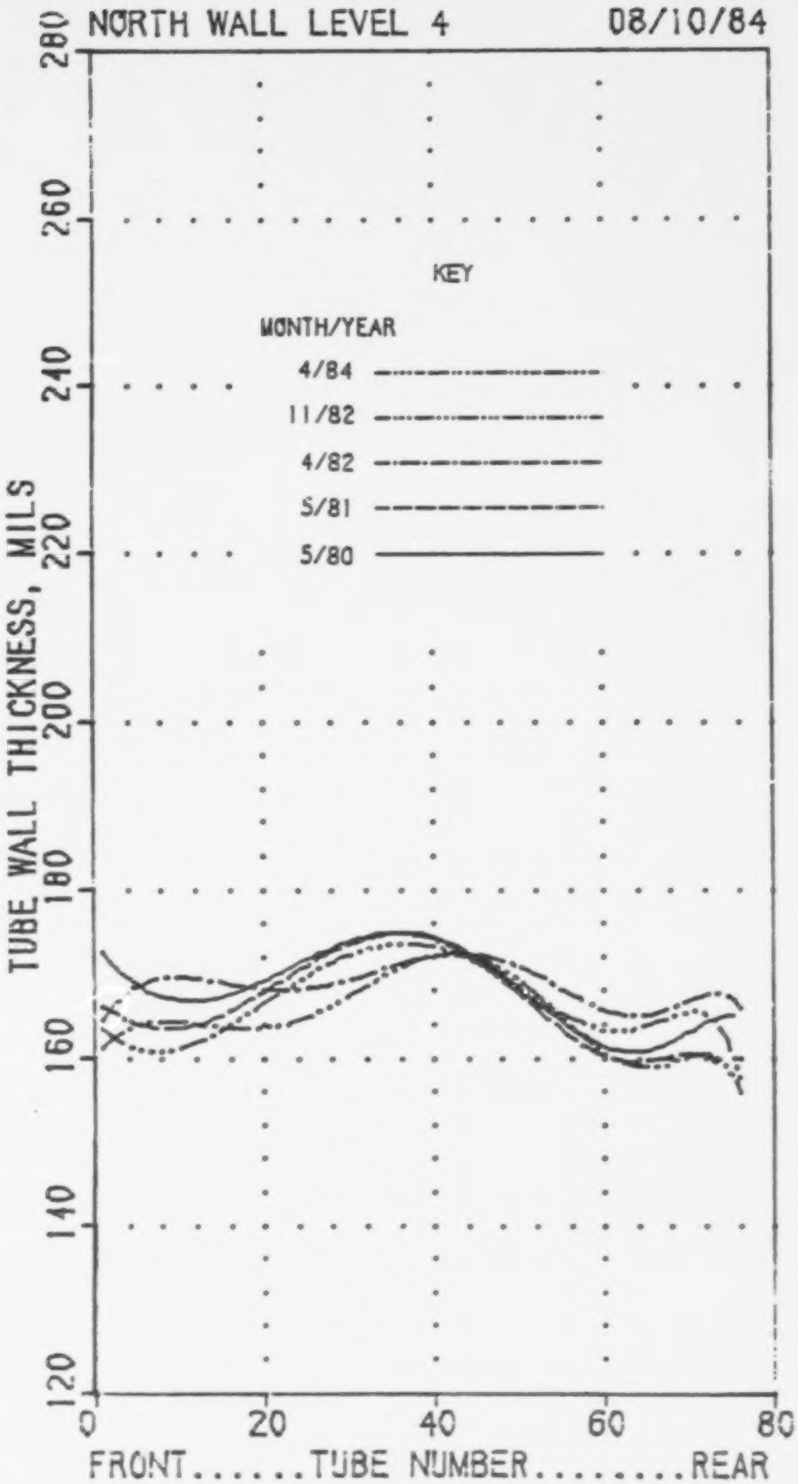
Tube Wall Thickness History, North Wall, Level 1 (Smoothed Form)



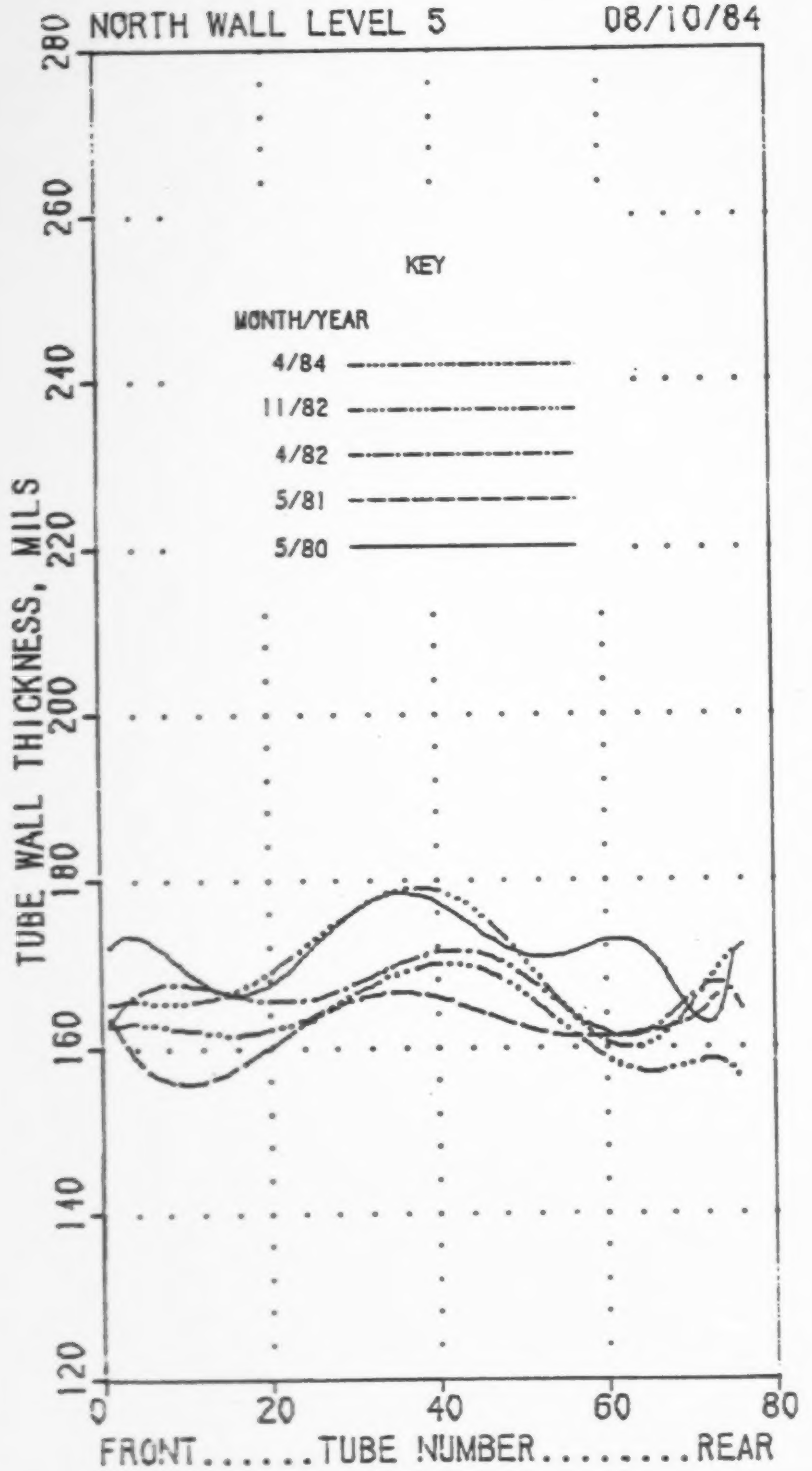
Tube Wall Thickness History, North Wall, Level 2 (Smoothed Form)



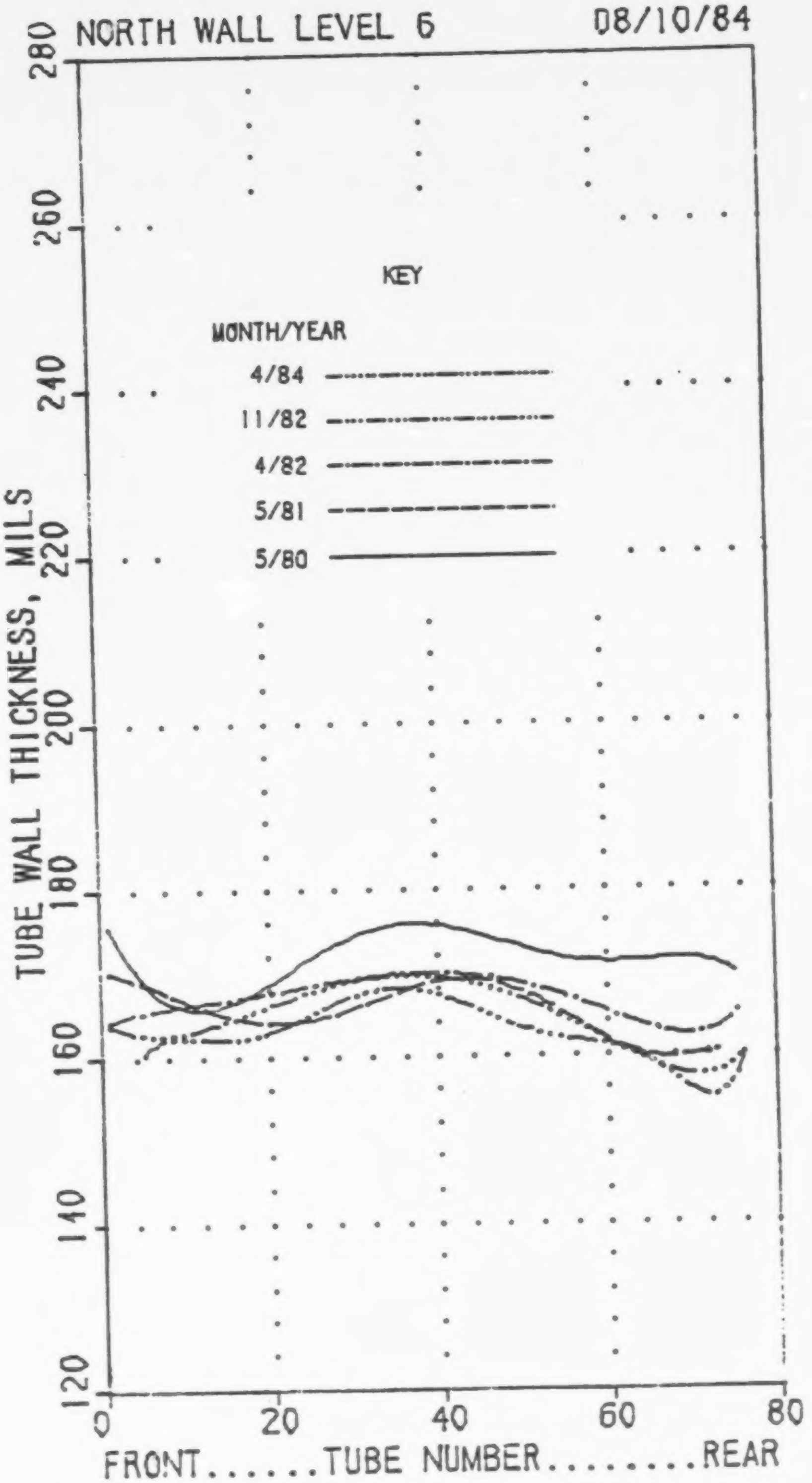
Tube Wall Thickness History, North Wall, Level 3 (Smoothed Form)



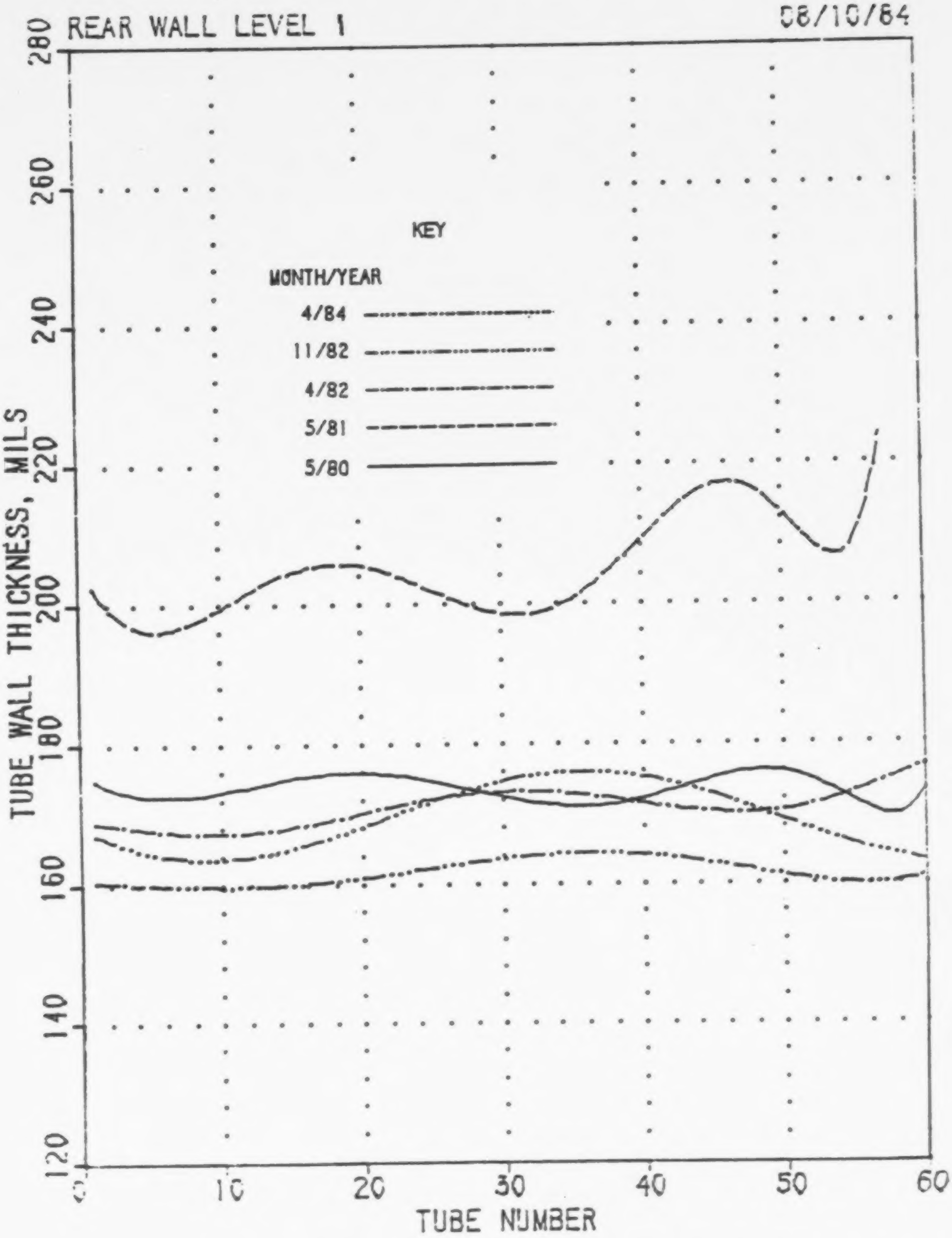
Tube Wall Thickness History, North Wall, Level 4 (Smoothed Form)



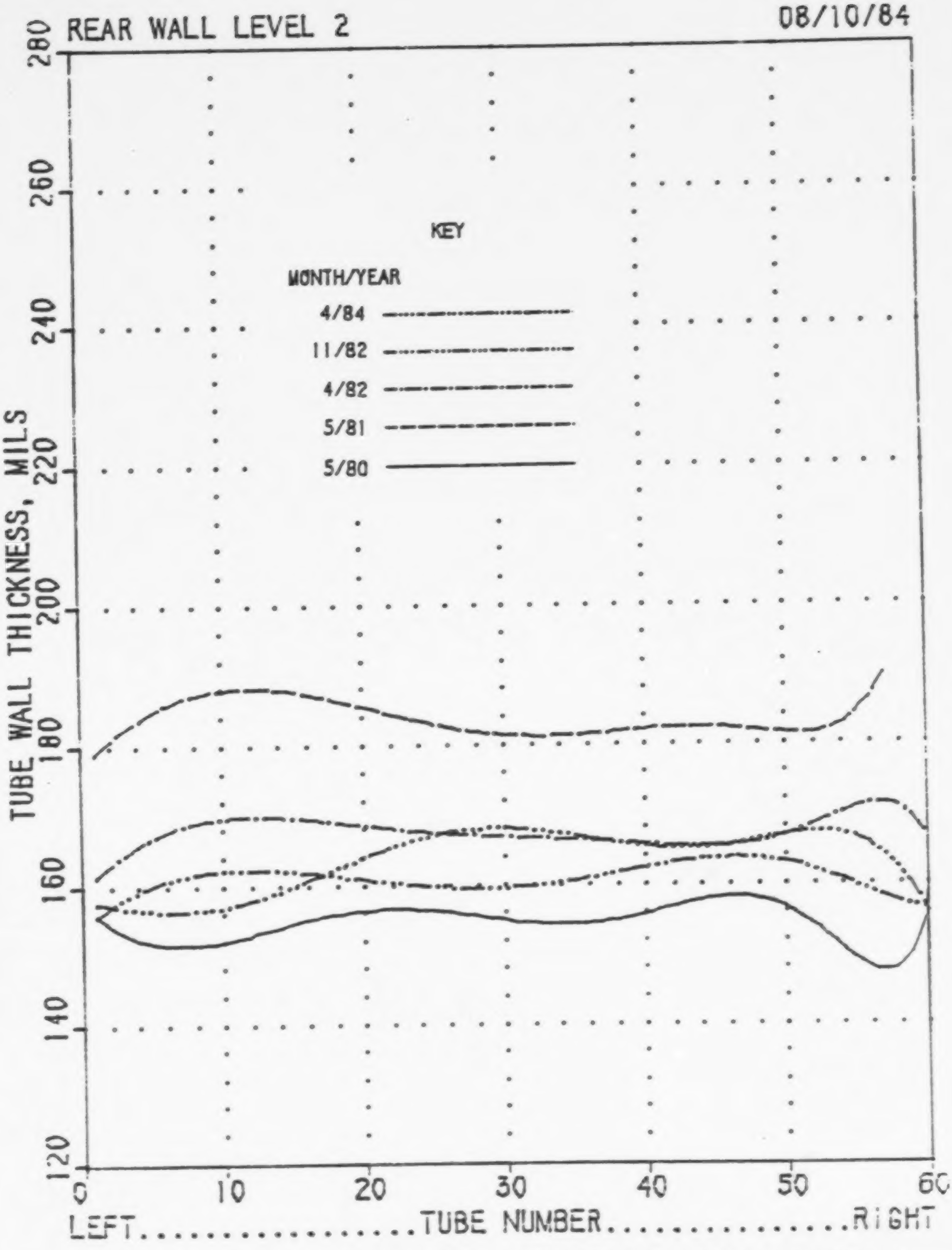
Tube Wall Thickness History, North Wall, Level 5 (Smoothed Form)



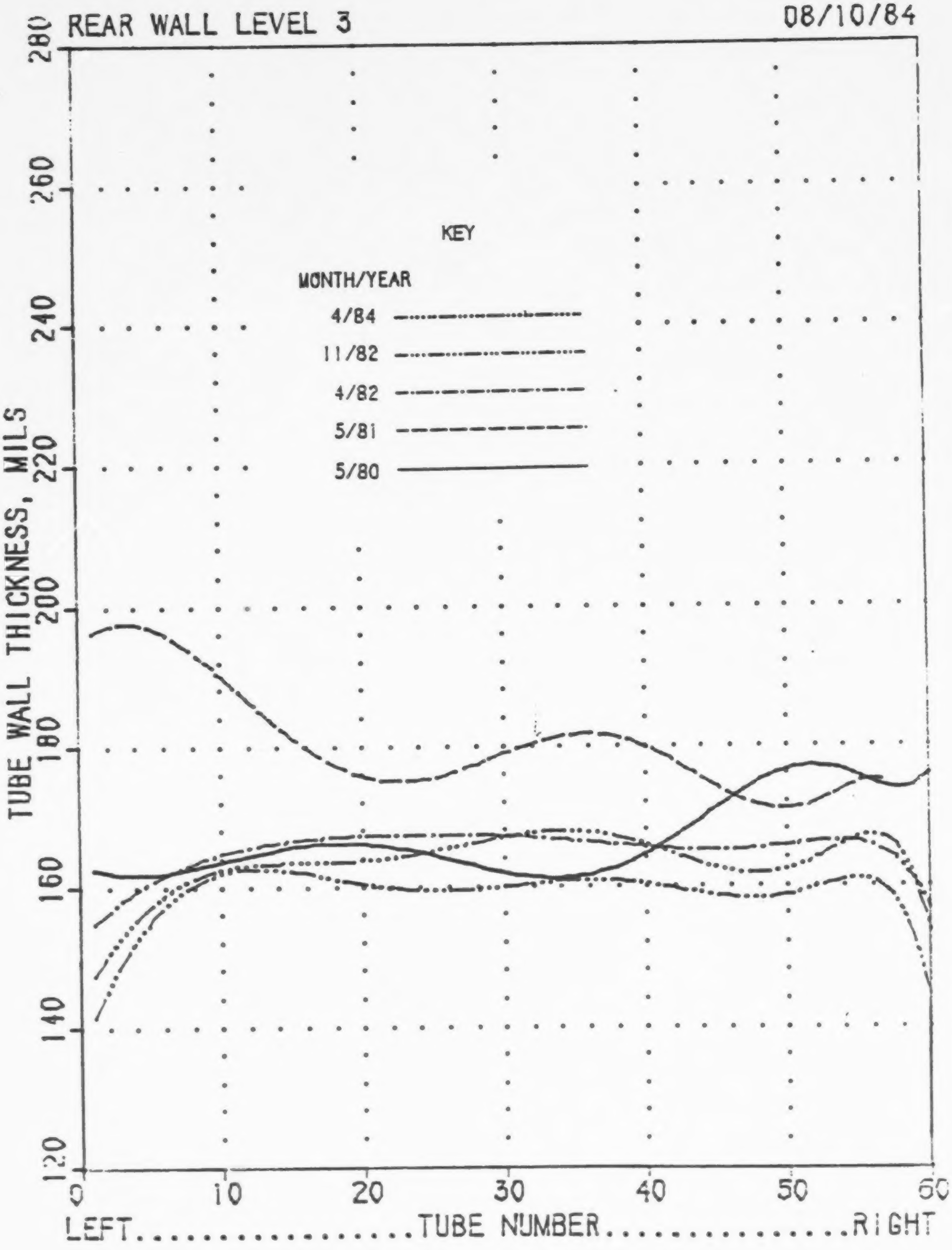
Tube Wall Thickness History, North Wall, Level 6 (Smoothed Form)



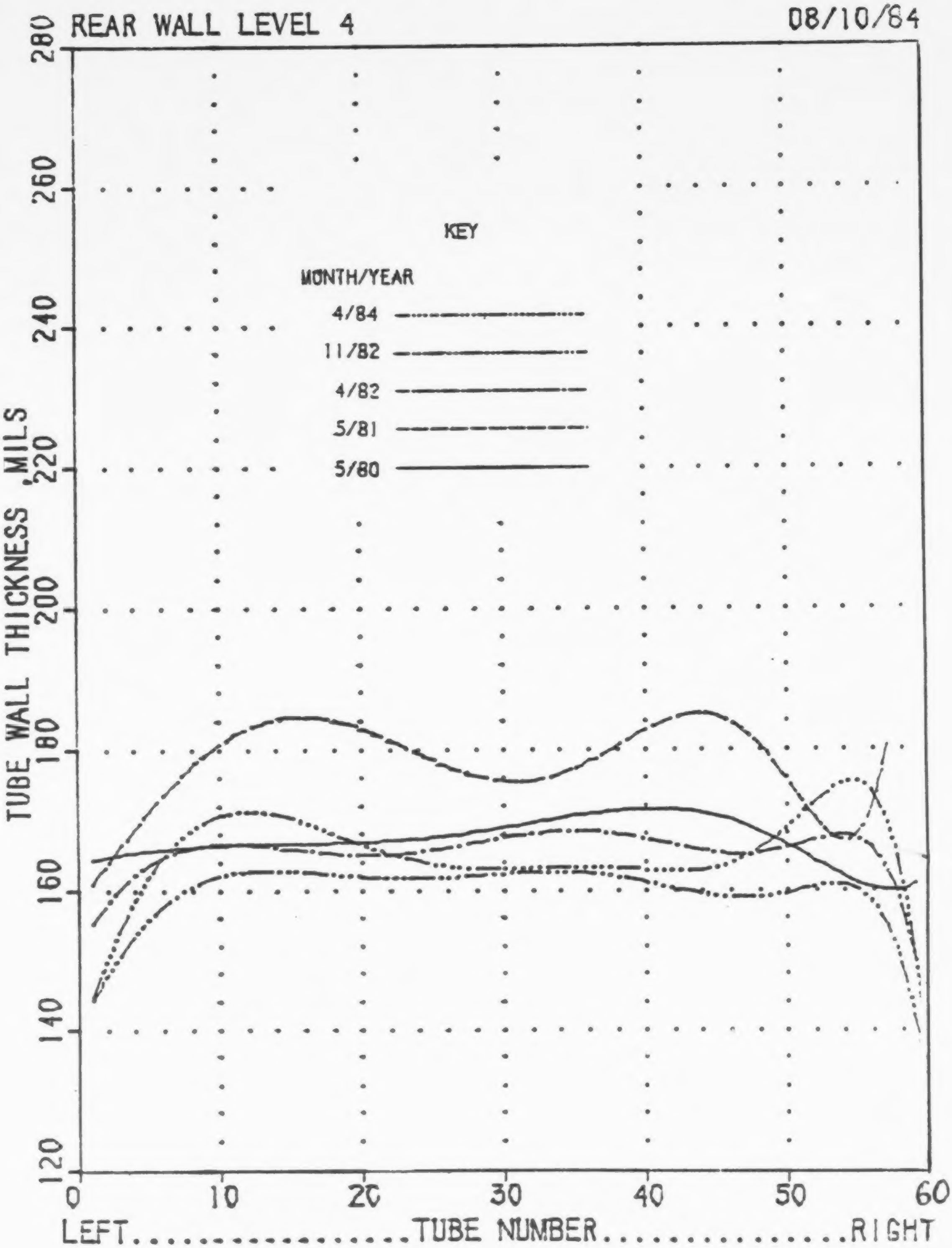
Tube Wall Thickness History, Rear Wall, Level 1 (Smoothed Form)



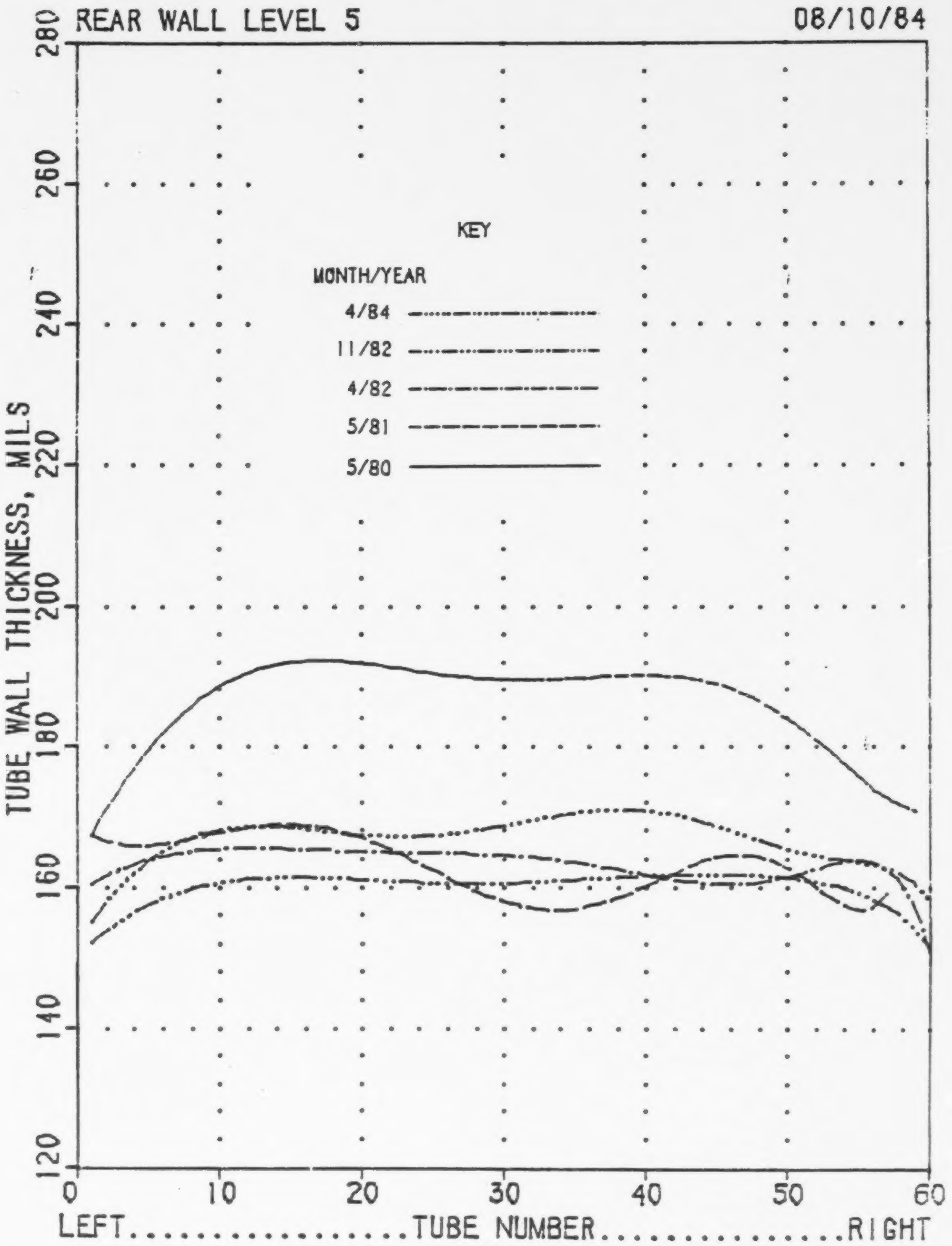
Tube Wall Thickness History, Rear Wall, Level 2 (Smoothed Form)



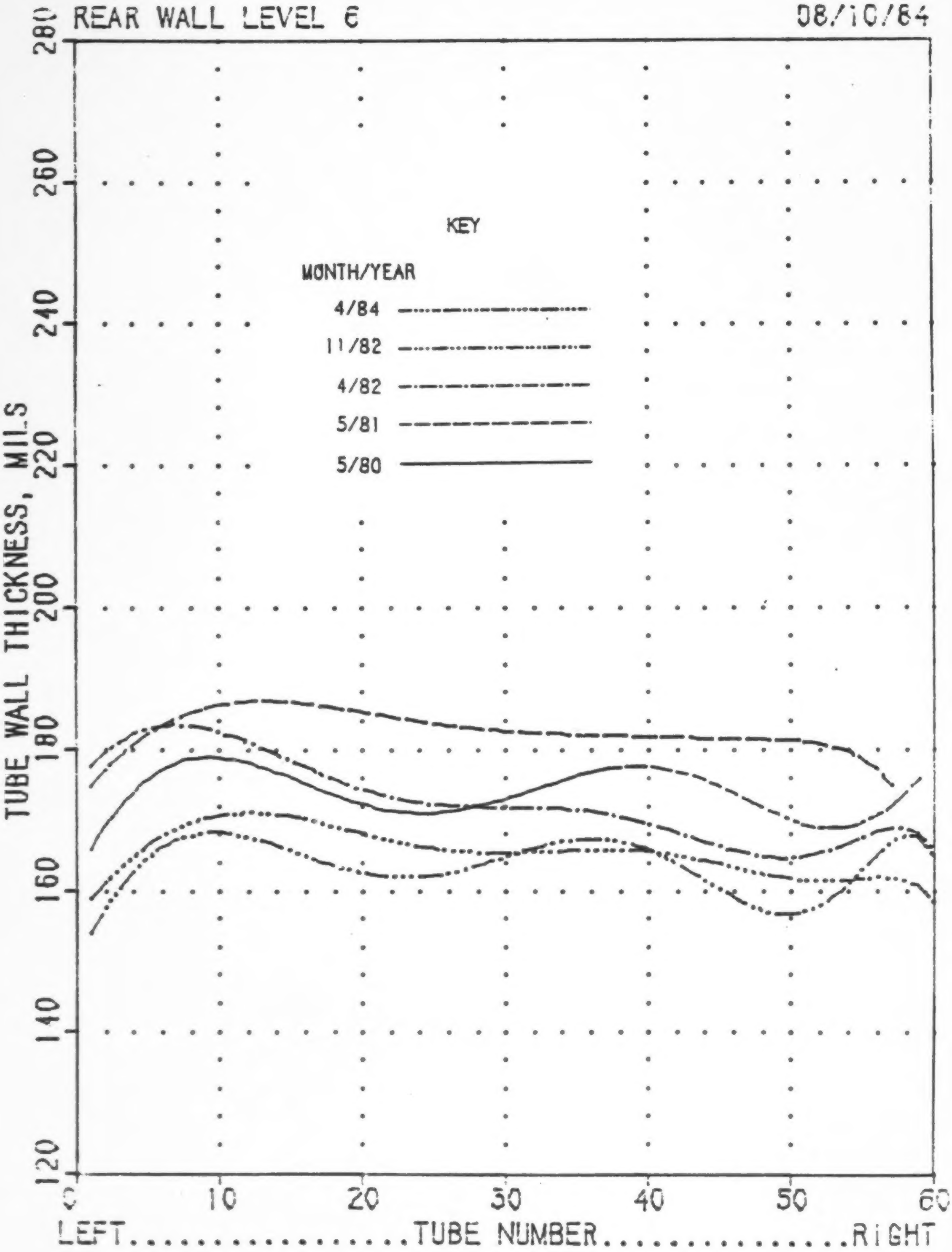
Tube Wall Thickness History, Rear Wall, Level 3 (Smoothed Form)



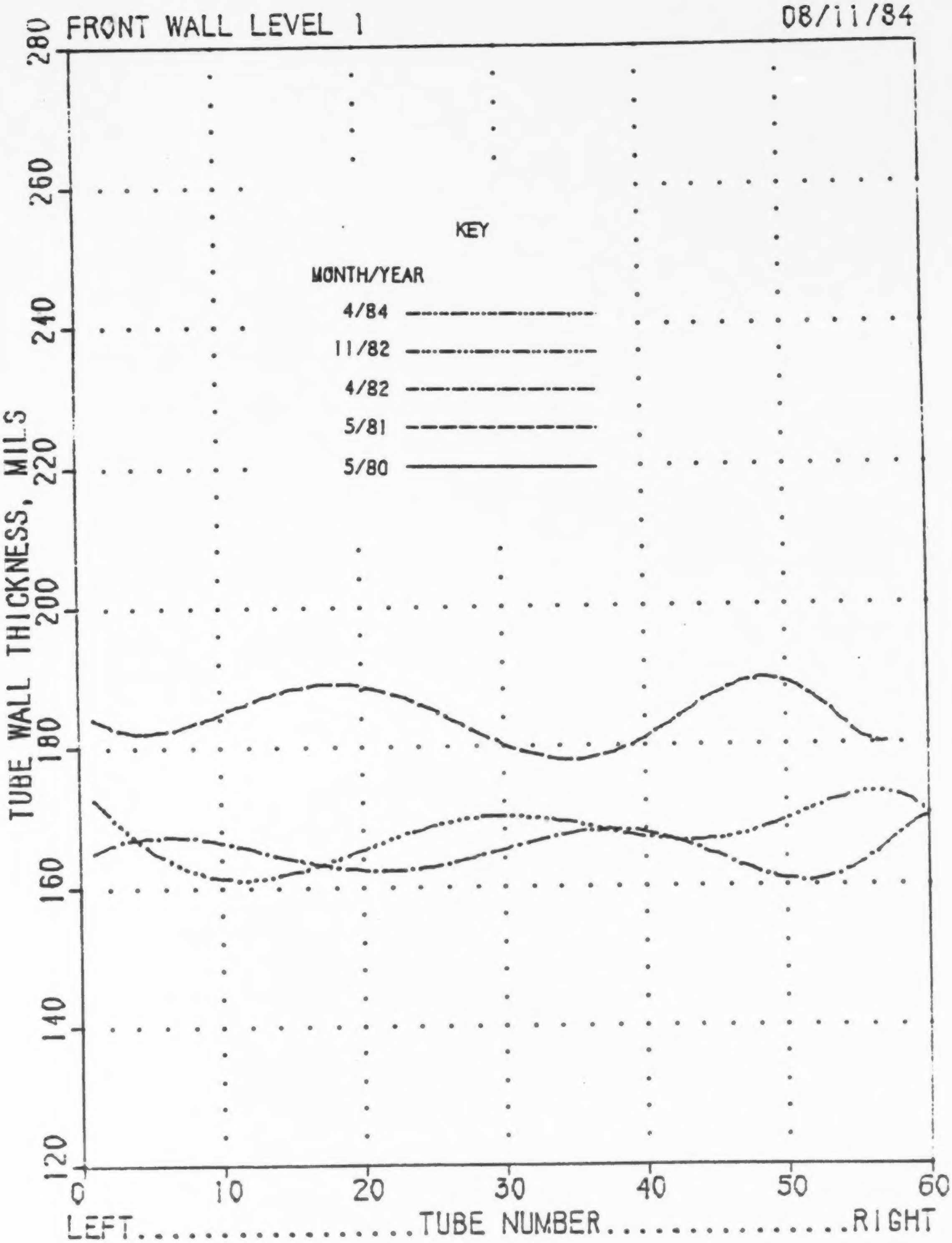
Tube Wall Thickness History, Rear Wall, Level 4 (Smoothed Form)



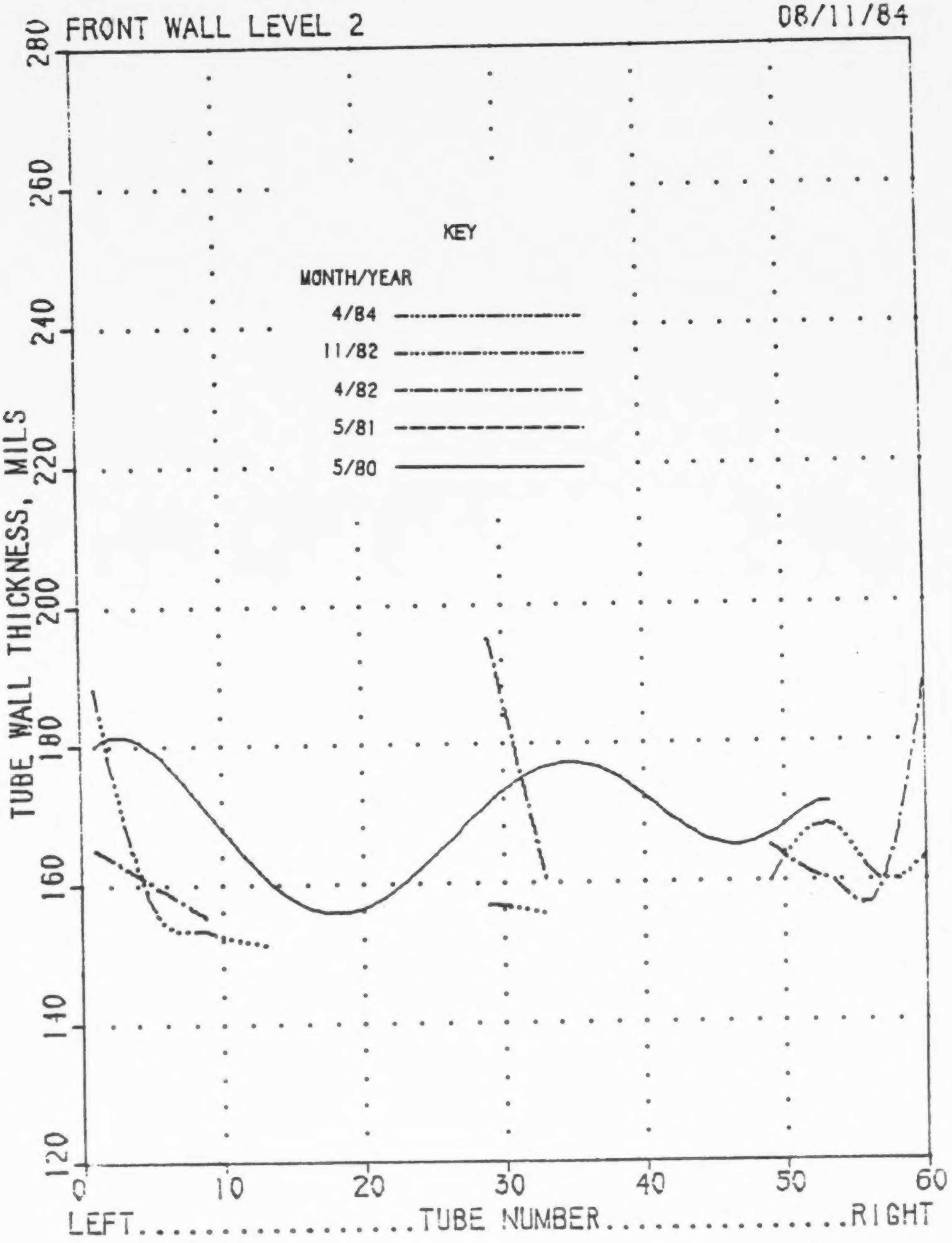
Tube Wall Thickness History, Rear Wall, Level 5 (Smoothed Form)



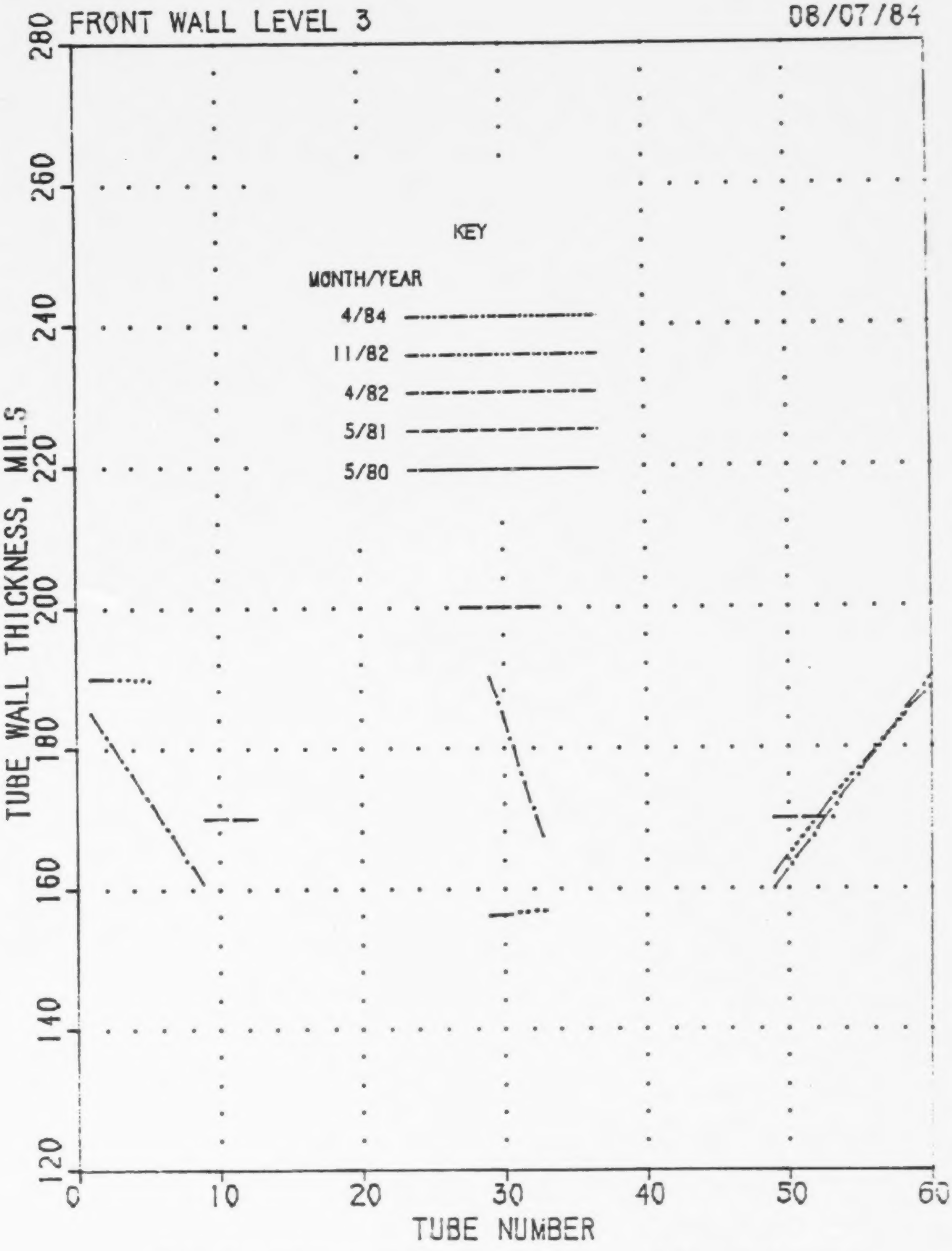
Tube Wall Thickness History, Rear Wall, Level 6 (Smoothed Form)



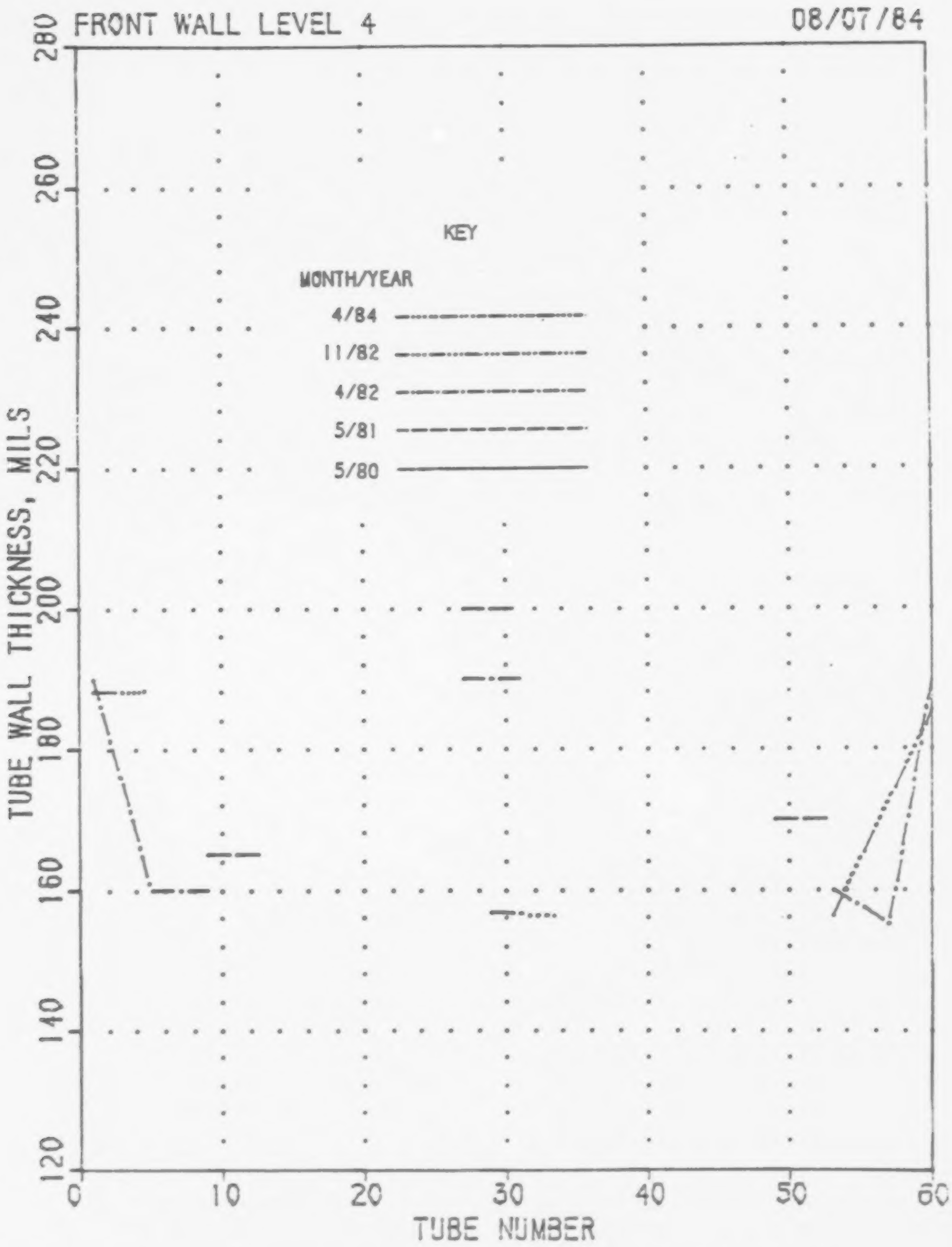
Tube Wall Thickness History, Front Wall, Level 1 (Smoothed Form)



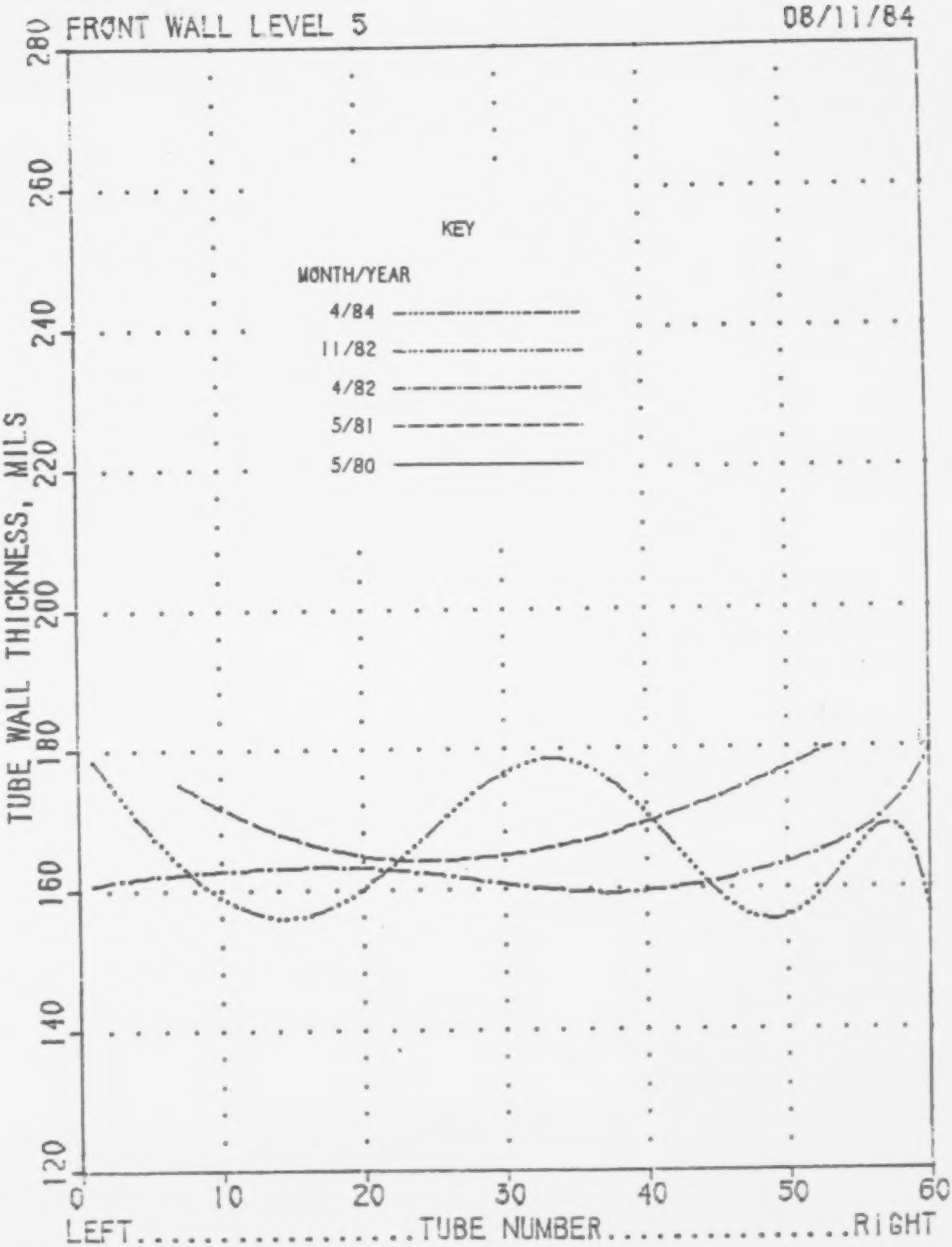
Tube Wall Thickness History, Front Wall, Level 2 (Smoothed Form)



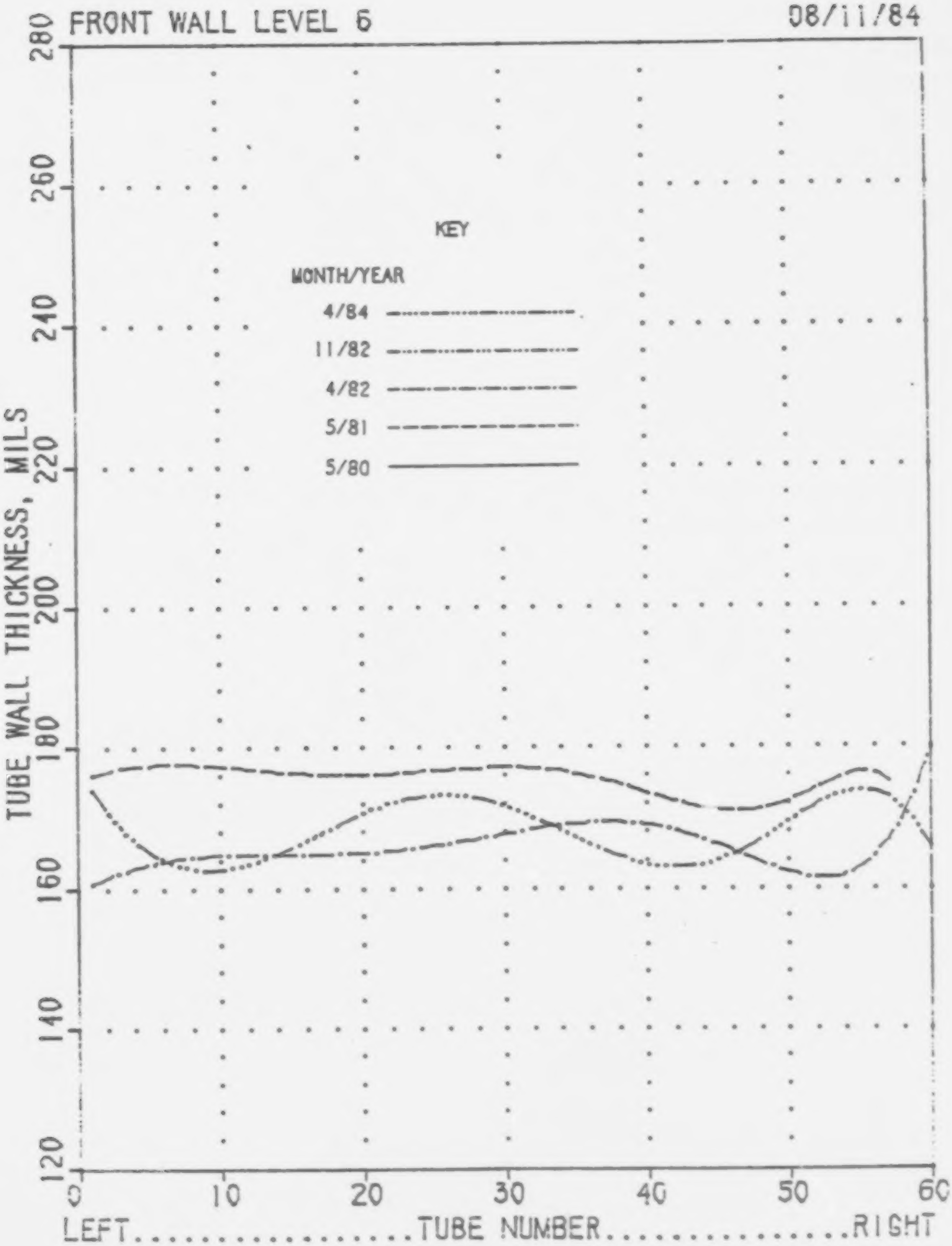
Tube Wall Thickness History, Front Wall, Level 3 (Smoothed Form)



Tube Wall Thickness Histroy, Front Wall, Level 4 (Smoothed Form)



Tube Wall Thickness History, Front Wall, Level 5 (Smoothed Form)



Tube Wall Thickness History, Front Wall, Level 6 (Smoothed Form)

APPENDIX F

DATA QUALITY

This program was initiated prior to the implementation of EPA's agency-wide approach to quality assurance, as delineated in the document "Interim Guidelines and Specifications for Preparing Quality Assurance Project Plans," QAMS 005/80, December, 1980. Therefore a formal Quality Assurance Project Plan was not prepared for this program following EPA's current format. However, the assurance of quality measurement data was recognized as a key element throughout the program. Detailed measurement procedures and quality control/quality assurance procedures were detailed in the Measurements Protocol which was prepared and approved by the EPA Project Officer prior to the initiation of measurements.

This program involved a large number of measurements, as described in the Measurements Protocol. Many of these measurements were not used to establish absolute emissions levels, but were used as relative indicators of burner operating conditions or performance. These measurements were subjected to limited quality control procedures to ensure the data satisfied the measurement needs. More detailed QC/QA procedures were applied to the measurements that were critical to establishing the emissions performance of the DMB. These critical measurements included:

1. Continuous emissions monitoring of NO_x, SO_2, O_2, CO, CO_2, and hydrocarbons

2. Particulate and particle size

3. Solids analysis of coal and ash

4. SO_3

5. EPA Reference Methods 3, 6, and 7 used to verify the accuracy of the continuous monitors.

Specific QA/QC procedures applied to these measurements included:

1. Use of EPA or other standard procedures for all measurements
2. Calibration of key test equipment components on a routine basis
3. Replicate measurements to evaluate precision
4. Evaluation of measurement accuracy using independent measurements.
5. Routine analysis of EPA Emissions Measurements and Support Laboratory Audit Samples.
6. Systems and performance audits conducted by an independent EPA QA contractor.

Key results of these QA/QC procedures are discussed below. In general, no quality related problems were identified, and the data can be applied without qualification. The one exception is the results of the Level I environmental assessment conducted during the baseline tests conducted by Acurex. The results of an independent audit indicated that the organic and water quality results are of very limited usefulness.

In addition to the Level I audit, the EPA QA contractor, RTI conducted performance and systems audits of EER's measurements in June, 1980 and March, 1981. Table F-1 summarizes the audit procedure. The results are illustrated in Table F-2. Overall, EER"s procedures were judged satisfactory. Recommendations for minor improvements in test procedures were made by RTI. These recommendations were incorporated in EER's standard procedures.

The continuous monitoring system was installed and operated following the guidelines of EPA Performance Specifications 2 and 3. The monitors

TABLE F-1. SUMMARY OF TEST METHODS AND AUDIT PROCEDURES

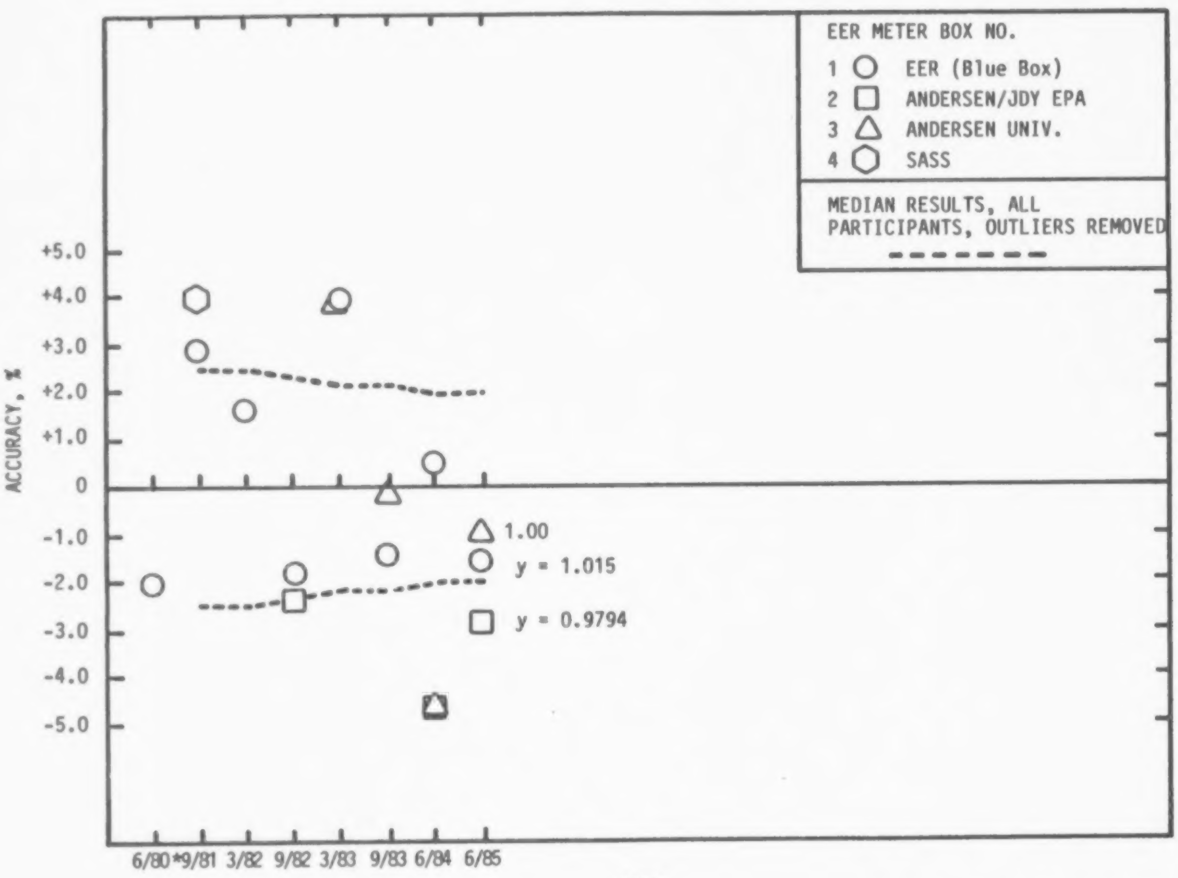
TEST METHOD	SYSTEMS AUDIT PROCEDURE	PERFORMANCE AUDIT PROCEDURE
Continuous Monitoring Instrumentation	Review of facilities and equipment. Review of calibration and maintenance procedures. System documentation.	Analysis of standard compressed gases introduced at sampling probes. Individual probe flow rates checked against NBS.
EPA Reference Methods 2, 3, 4, 5, 6, 7, 8	Observation of sample collection and analysis. Review of data forms, calibration, and documentation. Check of equipment for conformance to EPA specifications.	Method 3: Analysis of standard gases. Method 5: Check of gas meter accuracy against calibration orifice. Methods 6 and 8: Analysis of standard sulfuric acid solutions. Method 7: Analysis of standard NO_2 samples in absorbing solutions.
Controlled Condensation for SO_3	Observation of sample collection. Review of data forms, test procedure, equipment, and documentation.	
In-Stack Cascade Impactor for Particle Size	Observation of loading of impactor with substrates, sample collection, and unloading of impactor.	

TABLE F-2. EER AUDIT RESULTS

TEST PROCEDURE AUDITED	AUDIT PROCEDURE	RESULTS OF AUDIT
EPA Method 3	Analysis of standard gases by EER	O_2: 1 to 1½% low CO_2: 2 to 4% high
EPA Method 5	Test of dry gas meter accuracy with calibrated orifice	2% low
EPA Method 6, 8, and Controlled Condensation (SO_3)	Titration of standard acid solutions	2% low to 0.4% high
EPA Method 7	Analysis of standard absorbing solution	6% to 10% low
Particle Size Distribution	Observation of sample collection	Procedure acceptable
Continuous Monitoring System	Analysis of standard gases	NO_x: 0% SO_2: 2.5% high CO : 0.6 to 12% high CO_2: 4% low O_2 : 5 to 10% low HC : 7.6% high for gas sample of from 4 to 37 ppm C_3
	Test flow rates of probes against NBS flow meter	<10% error

routinely calibrated with compressed gases traceable to NBS standards following EPA Protocol 1. The monitors were calibrated once per day during the long term tests and more frequently during the short term optimization tests. These calibrations were used to monitor instrument drift and as a measure of precision. Relative accuracy of the analyzers was verified to be within specifications 2 and 3 during the baseline and 30 day DMB evaluations using EPA Reference Methods.

EER routinely analyzes audit samples from EPA EMSL for Methods 3, 5, 6, and 7 and for coal analysis. Coal samples are also submitted to Hazen Laboratories. Hazen performs coal and ash analysis as a subcontractor to EER. Figures F-1 through F-7 show the quality control charts maintained by EER of the accuracy of the audit sample analysis.



ACCURACY QUALITY CONTROL CHART

*Audit by RTI FOL EPA IERL

Figure F-1. EPA EMSL Method 5 Audit.

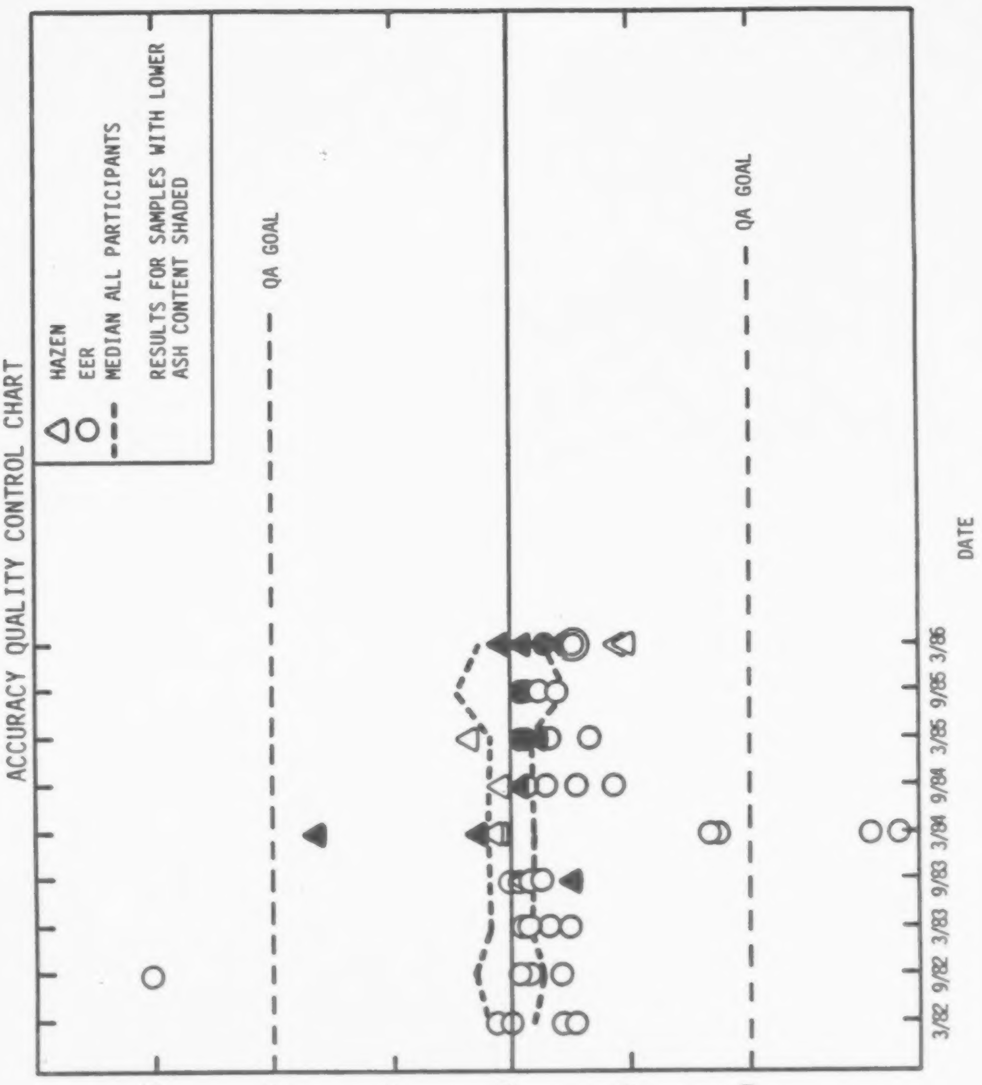
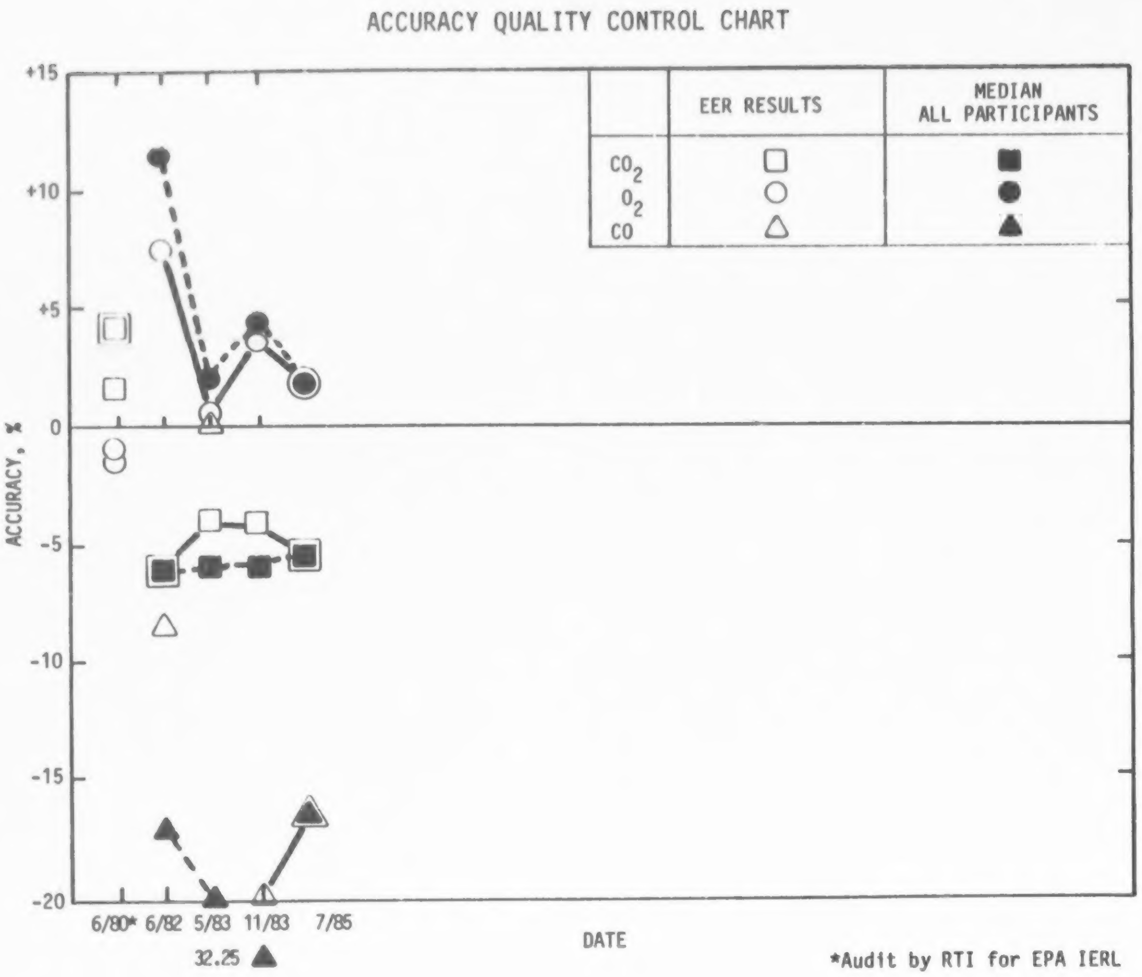


Figure F-2. EPA coal audit ash analysis.



*Audit by RTI for EPA IERL

Figure F-3. EPA EMSL ORSAT Audit.

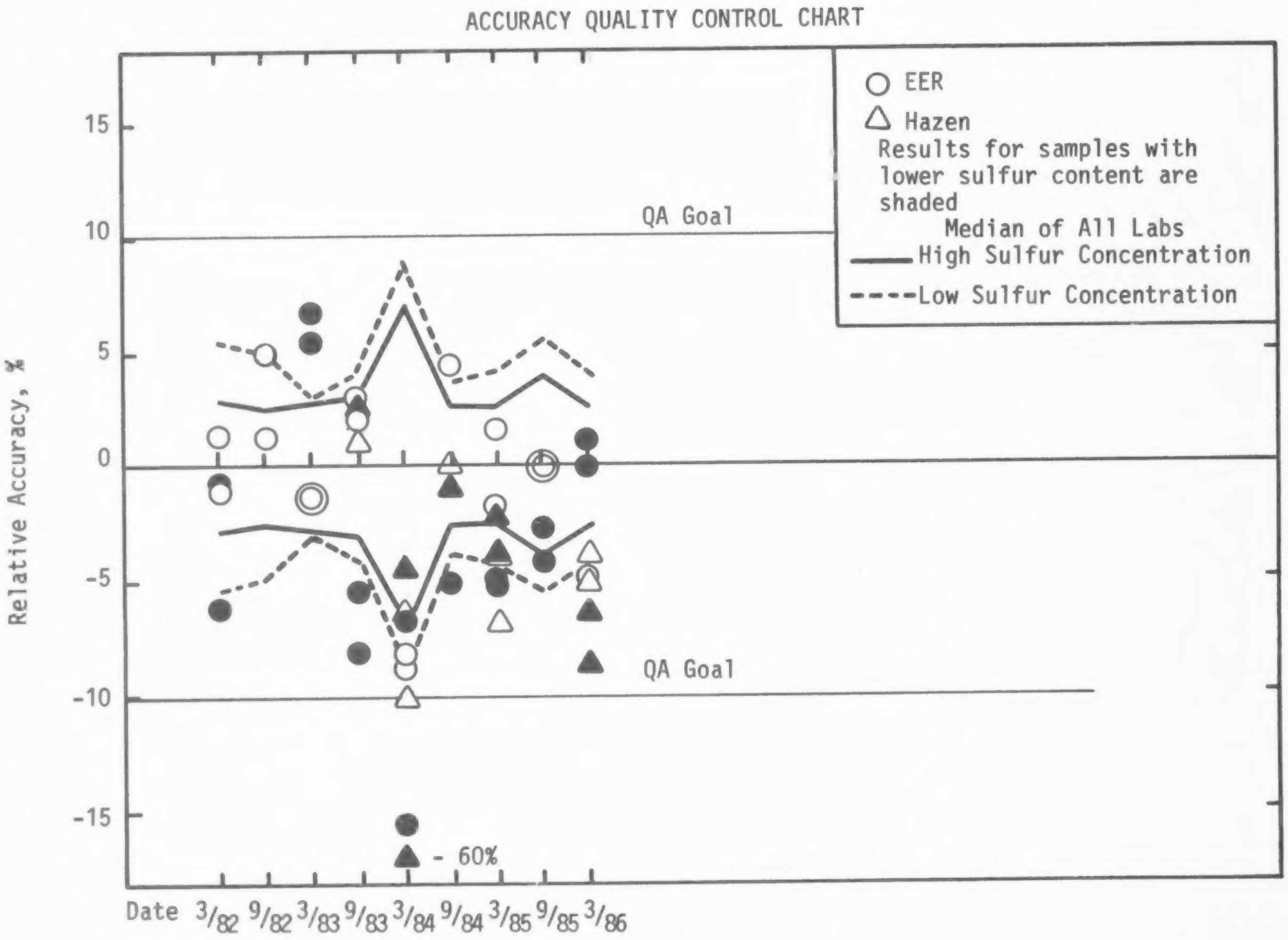


Figure F-4. EPA EMSL coal audit sulfur analysis.

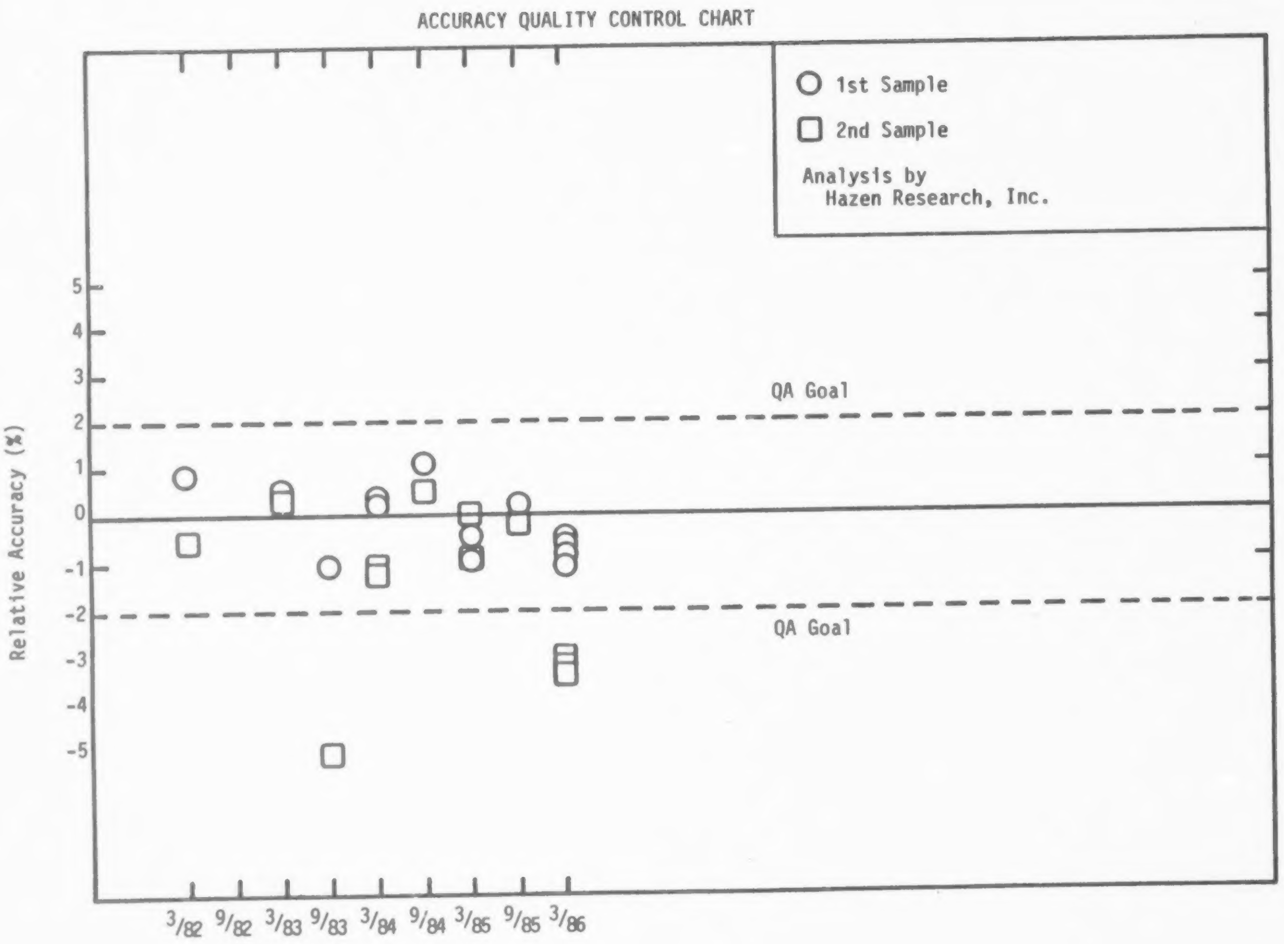


Figure F-5. EPA EMSL coal audit heating value analysis.

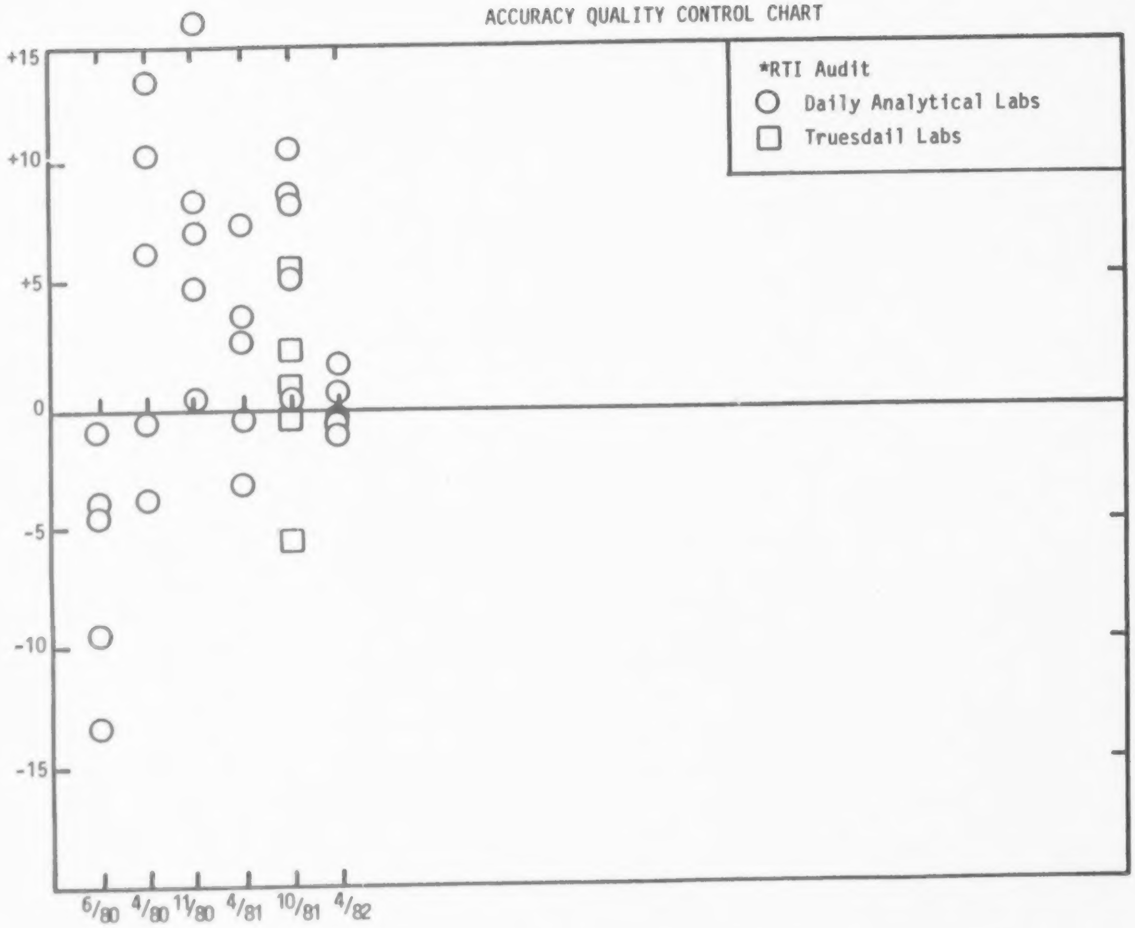


Figure F-6. EPA EMSL NO_x audit.

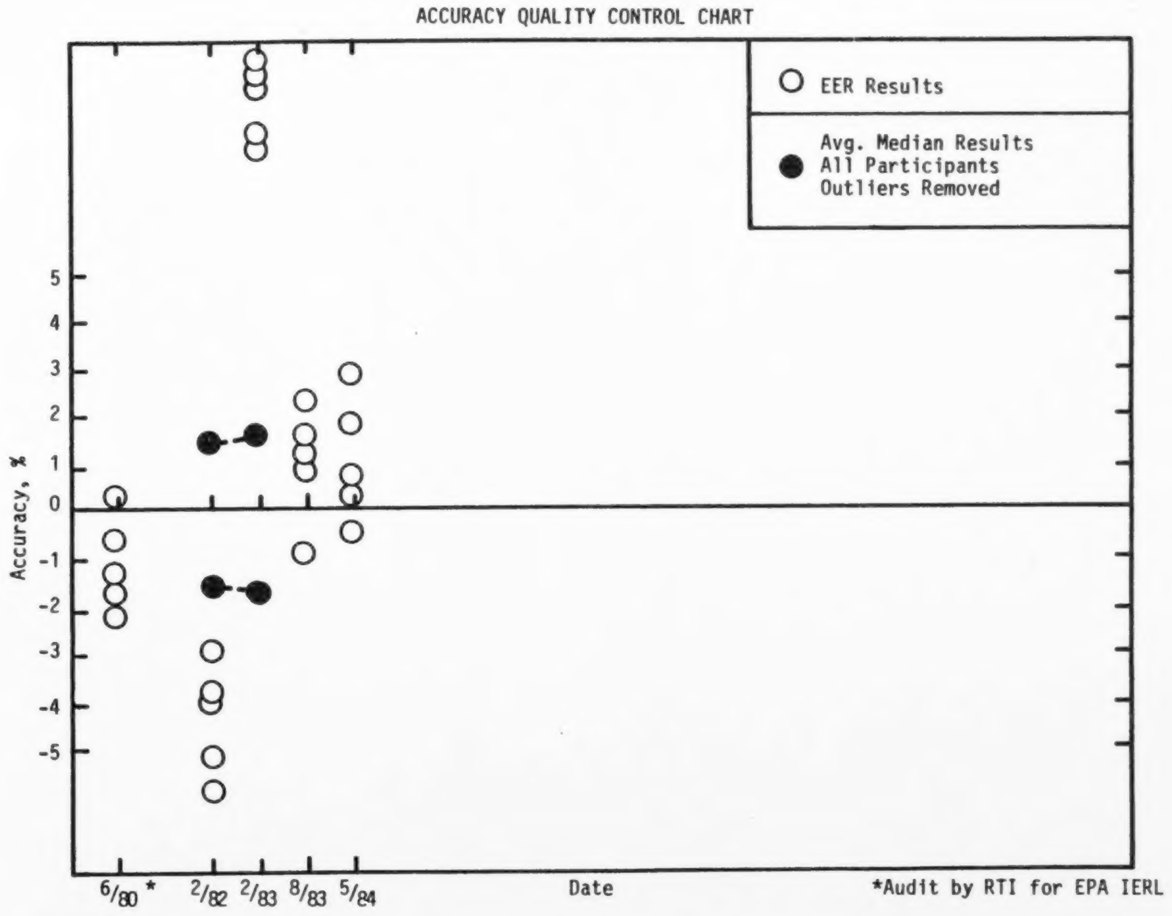


Figure F-7. EPA EMSL SO_2 audit.